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ABSTRACT

The objective of this thesis was to determine whether hourly
departures in building heat loss given by a simplified degree
day approach has a significant effect on the selection of an
optimum collector size for the solar system. A numerical model
was to do simulation studies. Using the results from this
simulation an optimum collector size was determined from the
energy requirements given by each model and a comparison made
between the simulations and the degree day approaches.

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

ENVIRONMENTAL INFLUENCES IN THE SIMULATION

OF A SOLAR SPACE HEATING SYSTEM

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

by

DOUGLAS M. BROOKS

NORMAN, OKLAHOMA

1980

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ENVIRONMENTAL INFLUENCES IN THE SIMULATION

OF A SOLAR SPACE HEATING SYSTEM

A THESIS

APPROVED FOR THE SCHOOL OF METEOROLOGY

By

Claude E. Duchon

B. Pickington

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ENVIRONMENTAL INFLUENCES IN THE SIMULATION

OF A SOLAR SPACE HEATING SYSTEM

CHAPTER I

INTRODUCTION

Background

After about 35 years of limited development, solar energy
has recently become a viable and economically attractive energy sup-
plement, capable of reducing our reliance on increasingly scarce fos-
sil fuel. Complete systems are now being sold and installed that
have a storage medium with the capability to provide from one to three
days space heating requirements.

Such systems involve a mix of both solar and conventional
heating systems, since a solar system which provides all of the build-
ing heat demands is normally neither economically nor architecturally
attractive. Given the short term storage and the unpredictable nature
of the solar input, the size of the conventional system in this com-
bination must be sufficient to provide all of the energy demands of
the building under the most adverse conditions expected. The size of
the solar system, on the other hand, is determined primarily by the
marginal cost of the collector/storage system in comparison with the
cost of the conventional fuel saved.

1

2

The amount of fuel saved is, in turn, a function of the per-
formance characteristics of the solar system and the heat loss charac-
teristics of the building. In many studies published in recent years,
the optimum collector size, in an economic sense, has been determined
from numerical simulation of hourly collector performance and building
heat demand over a representative period. The usual method of model-
ing building heat loss in these studies has taken into account temper-
ature effects only. A value for the building heat loss per hour per
unit temperature difference is determined using the procedures out-
lined in the ASHRAE Handbook of Fundamentals [2] for the building con-
struction characteristics and climatological design parameters at the
location under study. It is this value and the hourly values of air
temperature which then determine the building heat loss in the simula-
tion. In actuality, these hourly values of building heat loss will
vary not only with changes in air temperature, but with the wind
through its effects on convective losses and air infiltration into
the structure, and with solar radiation effects on the exterior of
the structure.

Objective

Modeling building heat loss as a function of temperature
only, in effect the degree day method, has been shown [20] to be rea-
sonably accurate over a long period of time, but does not necessarily
accurately simulate the short term nature of building heat loss. The
objective of this study is to determine whether these hourly depar-
tures in building heat loss from the values given by a simplified

degree day approach have a significant effect on the selection of an
optimum collector size for the solar system. In order to pursue the
objective, a numerical model was developed which simultaneously sim-
ulates the hourly interactions between the solar system, the house,
and the surrounding environment, using both the simplified model and
an expanded parameter model which includes the effects of air movement
over the structure and the influence of radiation on the structure it-
self. Using the results from this simulation an optimum collector
size was determined from the energy requirements given by each model
and a comparison made between the two approaches.

CHAPTER II

SOLAR RADIATION AND METEOROLOGICAL DATA

The model developed for this study is designed to use a SOLMET [24] data tape for the input values of solar radiation and meteorological parameters. These data tapes, obtained from the National Climatic Center, contain hourly solar radiation data and meteorological observations.

The radiation values on these tapes are of two types. At stations with solar observation facilities, they are the observed values corrected for known instrumentation errors [24]. For those stations without solar observations, radiation values were modeled through a regression procedure based on local meteorological conditions and radiation values at the nearest station with observed values [24]. These regression modeled values were originally reported to be accurate within a standard error of +/- 1.7% per month when compared with observed values [24]. However, these values have recently been questioned by Hoyt [11] who reports the monthly errors may be as large as 7% at some stations. The SOLMET values are still apparently the most accurate estimate of hourly solar radiation, particularly when compared with the frequently used ASHRAE clear sky values which Felske [7] reports give large overestimates of available solar energy.

4

The SOLMET tapes with regression modeled solar data have values only for global radiation on a horizontal surface. These values must be separated into direct and diffuse components for solar system performance calculations and this separation was accomplished using the method developed by Liu and Jordan [14] and modified by Hunn [12] for computer analysis. In this method, Liu and Jordan's attenuation index, KT, is taken to be

$$KT=A*(1 - .1*CC)$$

where A is the transmissivity and CC the total opaque cloud cover in tenths. The diffuse component is separated from the global horizontal value through a correlation of Liu and Jordan's value for the ratio of diffuse to horizontal radiation, D/H, with the attenuation index, KT, by assuming this ratio can be applied to the hourly SOLMET values:

$$(D/H)=1-1.3575*KT$$

$$RHDU=(D/H)*RHT$$

where RHDU is the diffuse component and RHT the global horizontal radiation. The horizontal direct value is then obtained by subtracting the diffuse from the global and a direct normal value calculated from this value and the solar altitude:

$$RD=RHT-RHDU$$

$$RDN=RD/sin(\alpha)$$

where RD is the horizontal direct value, RDN the direct normal value, and alpha the solar altitude.

Those SOLMET stations which have corrected observed values also have values of direct normal radiation on the tape [24]. The

computer model developed for this study is designed to take either
type tape as input, and, depending upon an input flag, use either the
given direct normal value or one calculated as indicated above. The
other parameters from the SOLMET tapes used in this study are the
year, month, day, solar time, temperature, wind speed and direction,
and total opaque cloud cover.

The SOLMET data tape for Oklahoma City, with 13 years (1952-
1964) of hourly radiation and hourly meteorological data was used for
this study. To reduce the computer time necessary for the simulation,
the 13 year data set was used to produce an average year which consist-
ed of the 13 year average hourly value for each parameter for each of
the 8760 hours in a 365 day year. The average year values were trans-
ferred to disk storage for more ready accessibility and served as the
data set for all computer simulations. Beckman, et al. [3] have shown
that the use of an average year in the simulation of solar system
operation closely approximates the results obtained by using the full
data set and averaging the results, thus providing an accurate esti-
mate of long term performance.

CHAPTER III

HOUSE MODELS

Construction Characteristics

The houses considered in this study were modeled as single story residences with an unventilated attic beneath a peaked roof, and a full basement, as illustrated in Figure 1, in which the solar system storage vessel and conventional heating system were placed. The floor space for the three different house sizes considered, denoted as size I, II, and III, is 93 square meters, 135 square meters, and 180 square meters. Each house faces south and is taken to be a rectangular structure with width to length ratio of about 1:1.5 as suggested by Olgay [21] for optimum winter thermal performance in temperate to cool climates. The solar collector array is taken as an integral part of the south facing roof and has a slope from the horizontal of latitude plus 15 degrees, the value reported by Liu and Jordan [14] to be optimum for solar space heating. Since the model is designed to run for different locations and many collector areas, the remaining dimensions of the roof, such as the slope and area of the north roof, the area of the attic walls, and the height of the peak, are calculated in the program when the collector tilt and area of collector to be integrated into the roof are specified. Each house

8
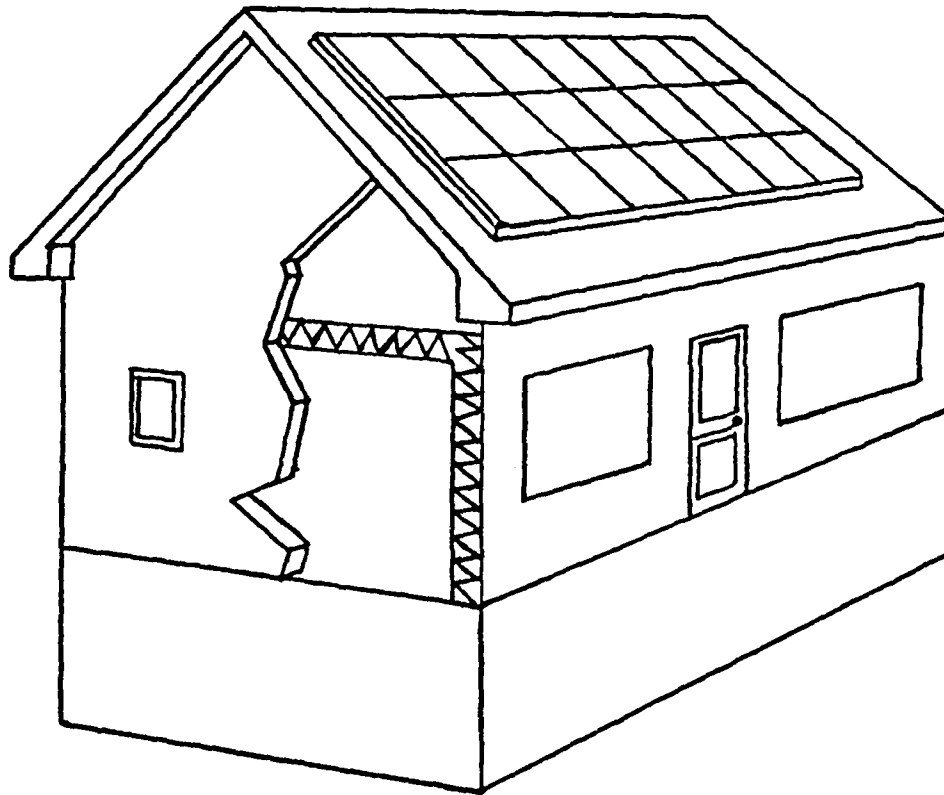
Figure 1.   Illustration of house model.

has a total window area of approximately 10% of the house wall area, and following Olgay [21], the distribution is weighted in favor of southern exposure for maximum solar gain in winter. The window area distribution is set at 60% of total window area on the south wall, 10% on the east and west walls, and 20% on the north wall. Each house has two entrances, one on the north side and one on the south side of the structure. The dimensions for each house size are given in Table A-1 of Appendix A.

Insulation

For each house size in the model, three different insulation and weatherstripping levels were considered, corresponding to poorly insulated, moderately insulated, and well insulated houses, and denoted as types I, II, and III. Type I consists of minimum wall and ceiling insulation, single pane windows with aluminum sash, no storm windows or doors, and minimum weatherstripping. Type II has moderate wall and ceiling insulation, double pane windows with wood sash, storm doors, and moderate weatherstripping. Type III has heavy wall and ceiling insulation, double pane windows with wood storm sash, insulated doors and storm doors, and is tightly weatherstripped. The construction characteristics and heat transmission coefficients (U-values) for each component of the three insulation levels are given for each type in Tables A-2 and A-3 of Appendix A.

CHAPTER IV

BUILDING HEAT LOSS MODELS

Introduction

Calculation of the energy requirements for the heating of a building may be carried out at a very simple level to provide approximate results or at increasingly more complex levels for more refined determination of system performance.

At the lower end of the scale is the heat loss per unit temperature difference method, as outlined in the ASHRAE Handbook of Fundamentals [2]. This method is based upon the assumption of steady state heat transfer through the building fabric as a function of inside to outside temperature difference. In this simplified model, denoted in this study as Model I, an overall building heat loss coefficient calculated using the methods outlined in the ASHRAE Handbook provides the basis for determination of energy requirements for space heating. This simplified method is the one most frequently used in engineering calculations and has served as the model for building heat loss in many studies of solar energy for space heating, for example the widely quoted study by Löf and Tybout [15].

At the upper end of the scale is the numerical simulation of building heat loss by the rigorous method of simultaneous solution

10

of the non-steady state balance equations for each hour for each component of the structure. This approach is presented in reference 20, which outlines the National Bureau of Standards' computer program for heating and cooling loads, a sophisticated model primarily used to perform design studies of heating and cooling systems for large structures. The degree of complexity of this approach is, however, very time consuming and a model at an intermediate level was developed for this study. Denoted here as Model II, it takes into account wind and solar radiation effects on the building, as well as temperature differences, and will be used to determine if these influences are important considerations in the simulation of a solar space heating system.

Model I

The heat loss from a house consists of the energy lost by transmission through the walls, basement, ceiling, and other exposed surfaces and by energy carried away by exfiltrating air. The determination of an overall building heat transmission coefficient, the heating load imposed by infiltrating air, and the combination of the two effects into an overall coefficient of heat loss per unit temperature difference are presented below.

Transmission Heat Loss

Transmission heat loss through a given building surface, under the assumption of steady state conditions, may be determined using the procedures outlined in the ASHRAE Handbook of Fundamentals [2]. Using a heat transmission coefficient (U-value) for the construction characteristics of the surface, the total heat transmission

12

through the surface is

$$Q = U*A*(ti - to) \tag{1}$$

Q = heat transfer rate, kJ/h

ti, to = temperature at inside/outside surface, C

A = total area of the surface, sq m

U = heat transmission coefficient, kJ/(sq m-h-K)

The heat transmission coefficient can be expressed as

$$U = 1/R$$

R = thermal resistance of the ith element in the composite structure, given by

R = x/k for homogeneous materials, where

x = thickness of the element, m

k = thermal conductivity of the element, kJ/(sq m-h-C)

R = 1/C for air spaces, where C is the thermal conductance

R = 1/hi, 1/ho at the inside and outside surfaces, and

h = the surface film conductance.

The surface film conductance, which accounts for convective and radiative losses at the surface, is determined experimentally for a given surface and can be expressed as

$$h = hc + hr$$

The term hc is an experimentally determined convective heat transfer coefficient and hr is a radiative transfer coefficient between the surface and its surroundings, given by

$$hr = \sigma*Fa*Fb*(T1^4 - T2^4)/(T1 - T2)$$

σ = Stefan Boltzman constant

Fa = dimensionless factor to account for the shape and orientation of the surface to its surroundings

Fb = dimensionless factor which accounts for the emission and absorption characteristics of the surface and its surroundings

T1, T2 = temperature of surface and surroundings, K

The radiation coefficient, hr, is about 1/5 the magnitude of the convective component of the surface film conductance and varies little [6] over the range of temperatures of interest, having only a 2% change with a 10 degree C change in temperature. A constant value of 14 kJ per sq m per hr per degree C [2] was used for this parameter in this study.

For a surface of given construction and thickness, the heat transmission coefficient, U, may be calculated for steady state conditions if the thermal conductivities, thicknesses, and surface resistances are known. The ASHRAE Handbook contains extensive tables of resistances, conductivities, and transmission coefficients for most building construction materials, determined from a vast amount of experimental and theoretical work. These tables were used to determine the U-values for the building components considered in this study.

Using the U-values determined from the ASHRAE tables, the total transmission heat loss through the building fabric per unit time may be expressed as

$$Q_t = (t_i-t_o)\{U_gA_g + U_dA_d + U_wA_w + U_cA_c\} + (t_i-t_g)U_bP \qquad (2)$$

where U and A refer to the heat transmission coefficients and surface areas, P is the perimeter of the house, and the subscripts g, d, w, c, b refer to window glass, exterior doors, exterior walls, ceiling, and basement, respectively. U_b is an effective heat transmission coefficient per unit length for the basement walls and floor, determined as

outlined in the ASHRAE Handbook for below grade basements, and the
value for Uc is an overall coefficient of heat transfer for the com-
bined ceiling and roof. The temperatures ti, to, and tg are the in-
side temperature, outside air temperature, and the ground temperature
at basement depth. If the expression is divided by (ti-to), a value
for the transmission loss per hour per unit temperature difference
can be expressed as

$$Q_t/(t_i-t_o) = U_gA_g + U_wA_w + U_dA_d + U_cA_c + \{(t_i-t_g)/(t_i-t_o)\}U_bP \qquad (3)$$

As suggested in reference 5, the ratio (ti-tg)/(ti-to) is denoted by
Kb and assumed constant, so that (3) becomes

$$Q_t/(t_i-t_o) = U_gA_g + U_wA_w + U_dA_d + U_cA_c + K_b U_bP \qquad (4)$$

Infiltration Heat Loss

The heat load due to infiltrating air can be determined
using the air change method outlined in the ASHRAE Handbook as

$$Q_i = \rho*C_{pa}*Vol*I*(T_i-T_o) \qquad (5)$$

ρ = density of infiltrating air

Cpa = specific heat of air, kJ/(kg-C)

Vol = building volume, meters cubed

I = number of building air changes per hour

ti, to = inside and outside air temperatures, C

The air change rate is a function of the density difference between
the inside and outside air due to temperature effects (stack effect)
and the static pressure effect of wind velocity on the structure. At
present there is no analytical procedure for calculating the exact
air infiltration into a building, though numerous studies have been

directed at this problem. Peterson [23] has reviewed the results of 20 years of research and produced an expression for the number of air changes per hour in residential structures from wind and stack effects for different levels of weatherstripping and building construction. The expression is

$$I = A + B*(ti-to) + C*V \qquad (6)$$

where I is the number of air changes per hour, (ti-to) the temperature difference, V the wind velocity, and A, B, and C are empirically determined constants for the level of weatherstripping and building tightness. Peterson's expression was used here for determining the air change rate and values of the constants for each of the three house types are given in Table A-4 in Appendix A. A value for the number of air changes per hour for Model I is calculated in the computer program for the building type specified from the design wind velocity from the ASHRAE Handbook and the average daily winter temperature, both of which are input parameters. The air change rate varies from about 0.4 for a tightly constructed house (Type III) to 1 for a loosely constructed house (Type I). With the air change rate thus specified, the infiltration heat loss can be expressed as a loss per unit temperature difference as

$$Qi/(ti-to) = \rho*Cpa*Vol*I \qquad (7)$$

Building Heat Loss Coefficient

The heat losses through transmission and infiltration can be combined to give an overall building heat loss per hour per unit temperature difference as

$$HL = (Qt + Qi)/(ti-to)$$

The hourly building heat loss is then

$$QLOAD = \begin{cases} HL*(ti-to) & \text{, for to<ti} \\ 0 & \text{, otherwise} \end{cases} \qquad (8)$$

where QLOAD is the total heat loss in kilojoules. Following the usual practice [26], a reference temperature (18 C) less than the inside air temperature is used to account for the existence of heat sources not included in the model, such as solar heat gain through the windows.

This simplified model provides an approximation to the hourly heat loss for the building. The difficulty with this representation is that it incorrectly predicts the time distribution of the heating load. Gutierrez, et al. [9] found that changes in the time distribution of load produced variations of as much as 17% in required auxiliary energy in a study of the use of solar energy for hot water. The study considered only hot water requirements, and only for a one month period, and so did not address the long term effects or space heating. The degree of departure of the Model I approximation from the heat loss given by a more complex model of space heating requirements will depend primarily upon the magnitude of the hourly differences in infiltration load from the constant rate assumed above, the effects of solar radiation on the building, and the variation of the surface film resistance with wind. These effects are considered in the second model of building heat loss used in this study.

Model II

In expanding the number of parameters in the building heat loss model the intent was to include, in addition to temperature, two

other major effects, wind and solar radiation, which act on the build-

ing. Steady state conditions for each hour of the simulation are

still assumed, so that heat capacity effects are not included. The

degree to which the inclusion of heat capacity effects would change

the results is uncertain, though McQuiston and Parker [18] suggest

they are significant only in structures of large thermal mass, which

is not the case in this study.

Radiation Effects

The effects of radiation on the building were simulated by

the replacement of outside air temperature with the sol-air tempera-

ture in computations of transmission heat loss. The sol-air tempera-

ture, first introduced by Mackey and Wright [17], is a fictitious

temperature that in the absence of all radiative exchanges would pro-

duce the same rate of heat transfer at the exterior surface as actual-

ly occurs with solar radiation acting on the surface. It can be ex-

pressed as

$$Te = To + \alpha I/ho - \varepsilon \Delta R/ho$$

where

Te = sol-air temperature, K

To = outside air temperature, K

I = total radiation incident upon the surface, kJ/(sq m-h)

α = absorptivity of the surface, dimensionless

ε = emissivity of the surface, dimensionless

ho = surface film conductance, kJ/(sq m-h-K)

ΔR = difference between long wave radiation incident on the surface and radiation from a black body at To, kJ/(sq m-h).

The last term has been shown by McQuiston and Parker [18] to be negligible in comparison to the first two and in practice the expression is simplified to

$$Te = To + \alpha I/ho.$$

The sol-air temperature is thus dependent upon the absorptivity of the surface and its orientation relative to the sun, as well as the outside air temperature. A value of 0.7 was taken as representative [24] of the absorptivity for the exterior building materials used in this study. The values for outside surface film conductance were those used in the computation of the overall heat transmission coefficient (U-value) for the surface under consideration. The solar radiation, I, incident upon the surface can be calculated [14] from

$$I = RDN*\cos\theta + 0.5*RDU*(1+\cos\beta) + 0.5*RHT*\rho*(1-\cos\beta) \qquad (8),$$

RDN = direct normal radiation, kJ/sq m

RDU = diffuse radiation, kJ/sq m

RHT = global horizontal radiation, kJ/sq m

β = tilt of the surface from the horizontal, deg

ρ = surface reflectivity, dimensionless, deg

θ = angle of incidence of direct radiation, deg.

The angle of incidence on the surface is given by [3]

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \qquad (9)$$
$$+ \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega$$
$$+ \cos\delta\sin\beta\sin\gamma\sin\omega$$

δ = 23.45*sin[360*(284 + n)/365], deg

n = day of the year

ϕ = latitude of the station, deg

β = tilt angle from the horizontal, deg

γ = surface azimuth angle, south = 0, east +, west - , deg

ω = $2\pi*(\tau - 12)/24$, the hour angle, deg

τ = solar time, h

Using (9), (8), and (7) the angle of incidence, incident radiation, and sol-air temperature are calculated in the simulation each hour the sun is above the horizon. The transmission losses are then taken as a function of these sol-air temperatures instead of the outside air temperature.

Solar radiation also influences the hourly building heat balance by the solar heat gain through the windows. If a simplified model of solar heat gain, with the absorptivity of the glass assumed negligible, is used, the rate of heat entry from solar radiation through the window glass may be expressed [21] as

$$SHG = RDN*TAUW*\cos(\theta) + 0.5*RDU*TAUD \qquad (10)$$

where RDN, RDU, and θ are as described previously, and TAUW and TAUD are the transmissivities of the glass for direct and diffuse radiation. As suggested by Parmelee, et al. [22] for vertical windows, the transmissivity for diffuse radiation is taken as a constant value of 0.70 for single pane and 0.62 for double pane windows. The transmissivity for direct radiation was approximated here by a constant value for incidence angles less than 60 degrees and as a linearly decreasing function of incidence angle for angles greater than 60 degrees. Figure 2 depicts the transmissivity of one, two, and three glazings for direct radiation as given by Duffie and Beckman [6] (solid lines) and the approximations used in this study (dashed lines). For this model,
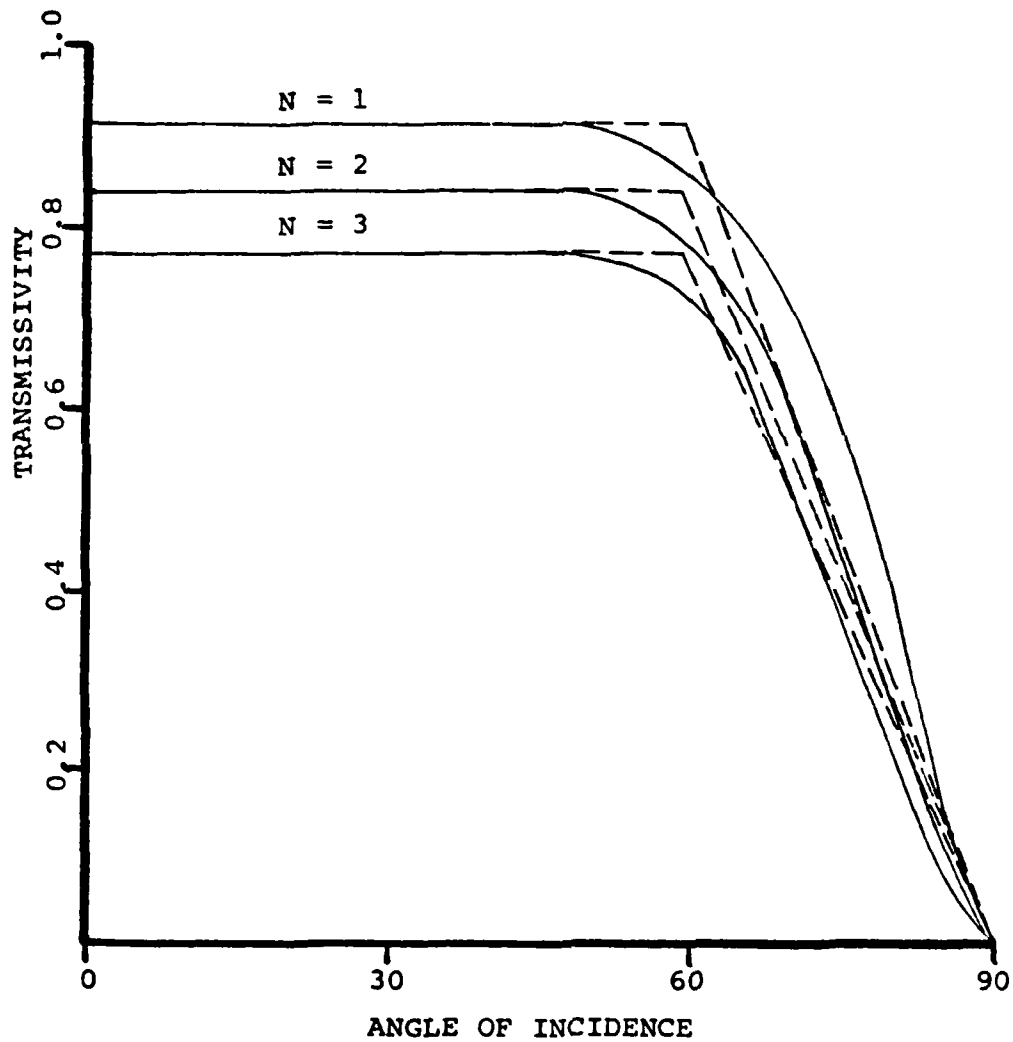
Figure 2. Transmissivity of 1,2, and 3 glazings as given by Duffie and Beckman (solid lines) and approximations used (dashed lines).

the windows are assumed to have no setback from the building surface,
and any effect from drapes or curtains on either the solar gain or
transmission loss through the windows is neglected. In addition, the
model assumes that window awnings which completely shade the windows
are installed on June 1 and remain in place until September 1, so that
only the diffuse component is considered during this period.

Wind Effects

The effect of variations in wind velocity on building heat
loss is considered in Model II by including its influence on surface
film conductance and on the infiltration rate. The convective com-
ponent of the outside surface film conductance is calculated for each
hour for each exposed surface as a function of wind speed and direc-
tion using an expression developed by Kimura and reported in reference
20. In this method, the air velocity close to the surface is

$$VC = 0.25*V \quad \text{for } V > 2 \text{ mps}$$

$$VC = 0.5 \quad \text{for } V < 2 \text{ mps}$$

for a relative wind direction less than 90 degrees, and

$$VC = 0.3 + 0.05*V$$

for a relative wind direction greater than or equal to 90 degrees,
where

$$V \text{ is the reported wind velocity, mps.}$$

The relative wind is calculated from the azimuth angle of the build-
ing surface and the reported wind direction as

$$RWD = ABS(WAZ - DIR) \quad \text{for } RWD < 180 \text{ degrees}$$

$$RWD = 360 - RWD \quad \text{for } RWD > 180 \text{ degrees,}$$

where ABS indicates the absolute value, RWD is the relative wind di-
rection, WAZ is the surface azimuth angle of the building surface
(facing north = 0), and DIR is the reported wind direction in degrees.
The convective component of the outside surface film conductance, hc,
is then calculated from

$$hc = 67.049(VC^{0.605})$$ (12)

For each hour of the simulation, the surface film conductance is cal-
culated from a convective component computed as outlined above and a
constant value of 14 kJ/(sq m-h-K) for the radiation component [2].
The heat transmission coefficient (U-value) for each building surface
exposed to the wind is calculated from this value of surface film con-
ductance and the same values of thermal resistance for the interior
construction used in Model I. The transmission heat losses for Model
II for each exposed surface are then calculated as a function of these
U-values and the sol-air temperature. Finally, infiltration losses
for Model II differed from Model I in that an air change rate was
calculated hourly as a function of wind and temperature from equation
6 and the infiltration heat loss calculated from equation 7.

Basement and Ceiling Transmission Losses

The transmission losses for the ceiling and basement for
Model II also differ from Model I. The transmission loss through the
ceiling was calculated as a function of attic temperature, calculated
from the following expression given in the ASHRAE Handbook [2];

Tattic = (Ac*Uc*Tc+Ta*Ar*Tr+Ta*Aw*Uw)/(Ac*Uc+Ar*Ur+Aw*Uw)   (13)

where A and U refer to the areas and U-values and the subscripts c, r,

w refer to the ceiling, roof, and attic walls respectively. Tattic, Tc, and Ta are the attic, ceiling and outside air temperatures. As suggested in reference 2, the ceiling temperature was taken as 1 degree C higher than the reference room temperature (20 degrees C for Model II). The outside air temperature was replaced by the applicable roof or siding sol-air value. Basement transmission losses were calculated for Model II by the method outlined for Model I, except that a value of the ground temperature was calculated for each day by assuming it was a sinusoidal function of the day of the year. Values of 283 K for winter and 294 K for summer from reference 20 for average values at Lake Hefner, Oklahoma were used to determine the amplitude.

Domestic Hot Water Energy Requirements

Energy requirements for hot water for both models were calculated by assuming a requirement of 75 kg of hot water per occupant per day, evenly distributed between the hours of 6 a.m. and 9 p.m. The number of occupants was assumed to be 4, 5, and 6 for house sizes I, II, and III respectively. The required hot water temperature was set at 60 degrees C (140 degrees F) and the temperature of the feed water from the main assumed to be equal to the ground temperature. The energy required for hot water is then

$$QSHW = \begin{cases} Mw*Cpw(Thw - Tg) , & 6<\tau<21 \\ 0 , & \text{otherwise} \end{cases} \qquad (14)$$

QSHW = hot water energy requirement, kJ/h

Mw = mass of water, kg/h

Cpw = specific heat of water, 4.189 kJ/(kg-K)

THW = hot water temperature, K

Tg = feed water temperature, K

Summary

This chapter has presented the models used for determining the building energy requirements for space and hot water heating. With Model I the hourly building heat requirements will vary only with temperature. With Model II the hourly heat requirements will vary with radiation and wind influences as well as temperature. The solar collector and storage models used in the hourly simulation of system performance will be discussed in Chapter V.

CHAPTER V

SOLAR COLLECTOR AND STORAGE MODELS

Collector Model

The solar collector modeled is a flat plate solar collector
with basic components as illustrated in Figure 3. An absorbing plate
is covered by one or more transparent cover plates to reduce convec-
tive heat losses and insulated to reduce transmission losses through
the back. The absorbing plate, coated with a material having high
absorptivity in the solar spectrum, heats up and in turn heats a fluid
flowing through the tubes in the plate. The amount of energy collected
is a function of the incident radiation, collector construction, the
fluid temperature, and the surrounding environmental conditions.

In this study, the collector is a water heating flat plate
collector with the following characteristics, taken from Duffie and
Beckman's book on solar energy thermal processes [6]:

1. The absorbing plate is a copper tube-in-sheet plate with
10 cm spacing between tubes and a non-selective coating which has a
constant absorptivity, independent of angle of incidence, of 0.95.

2. The glass covers (1, 2, and 3 covers are considered) are
water white glass with a thickness of 0.3125 cm and an extinction co-
efficient of 0.04 per cm.

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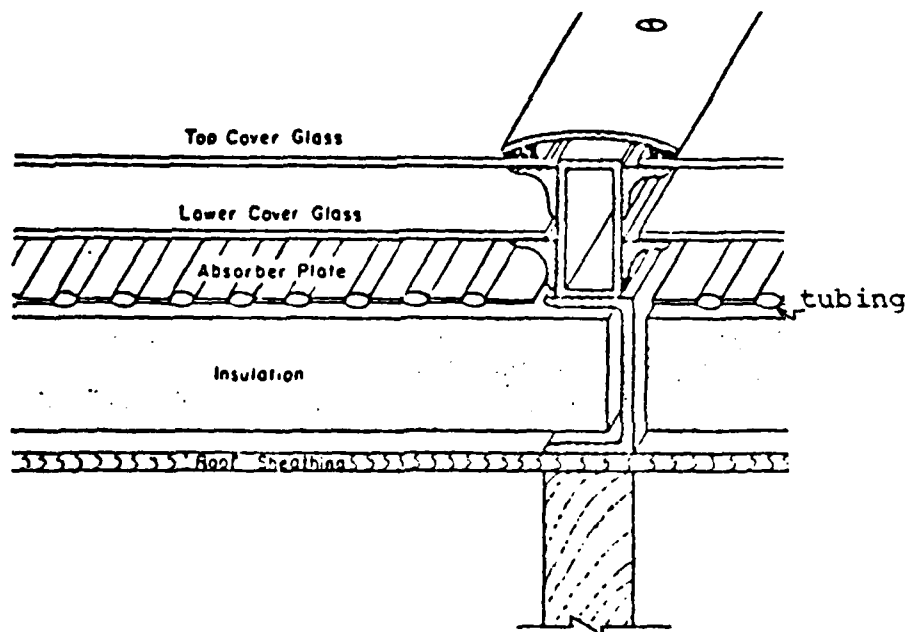
Figure 3. Solar collector cross section.

3. The absorbing plate has a plate-to-fluid heat transfer coefficient of 300 watts per sq meter per K.

Collector performance was modeled by the generalized flat plate performance equation proposed by Hottel and Whillier [10]. Duffie and Beckman [6] present a complete derivation of this expression, which relates the useful energy collected to the collector and environmental parameters as follows

$$QU = AC*FR*(S-UL*(TCI-TA)) \tag{15}$$

AC = collector area, sq m

FR = heat removal factor, dimensionless

S = radiation absorbed by the plate, kJ/(sq m-h)

UL = collector loss coefficient, kJ/(sq m-h)

TCI = inlet temperature of fluid, K

TA = ambient air temperature, K.

The useful energy, QU, is the energy collected by the heat transfer fluid in passing through the tubes in the collector plate. The radiation absorbed by the plate is a function of the incident radiation, the transmissivity of the glass covers, and the absorptivity of the plate. The incident radiation and the transmissivity were calculated as described in Chapter IV. The quantities FR and UL depend upon the construction characteristics of the collector, the heat transfer characteristics of the plate, the mass flow rate through the collector, and the number of collector covers. Values of UL, the collector heat loss coefficient, for the collector characteristic previously listed, were taken from graphs in Duffie and Beckman's book [6] as

UL = 7.2 kJ/(sq m-K) for 3 covers

UL = 14.4 kJ/(sq m-K) for 2 covers

UL = 28.8 kJ/(sq m-K) for 1 cover

The effect of the heat removal factor, FR, in equation 15 is to reduce
the calculated energy gain from the value given by assuming the fluid
temperature throughout the collector to be at the inlet temperature to
its actual value, given by a fluid temperature which increases as the
fluid flows through the plate. It can be expressed [6] as

$$FR = (FLO*CP/UL)*(1 - \exp(-UL*F'/(FLO*CP))) \tag{16}$$

FLO = mass flow rate per unit area, kg/sq-m

CP = specific heat of fluid, kJ/(kg-K)

UL = collector loss coefficient, kJ/(sq m-K)

F' = collector efficiency factor, dimensionless

As demonstrated by Duffie and Beckman [6], F' is primarily a function
of the physical characteristics of the absorber plate and can be con-
sidered a constant. Values were taken from Duffie and Beckman's book
for the collector characteristics considered here as

F' = 0.96 for 1 cover

F' = 0.98 for 2 covers

F' = 0.99 for 3 covers

Winn [24] reports that an optimum value for the mass flow rate per
unit area of collector can be determined from

$$FLO = F'*F'*UL/(2*CP*(F'-FR)) \tag{17}$$

Equations 16 and 17, with UL, CP, and F' are specified, form a set of
equations in the two unknowns, FLO and FR, which is solved in the pro-
gram using an iterative procedure for the optimal mass flow rate, FLO,
and the heat removal factor, FR. With these parameters specified,

equation 15 can be used to determine the useful energy collected for each hour the solar system is operated.

The collectors modeled in this simulation were "operated" when the temperature of the absorbing plate was heated to a temperature ten degrees higher than the storage tank temperature (discussed below). As derived in reference 6, the temperature of the plate for any given hour can be expressed as

$$TP = TA + S/UL = [S/UL-(TPP-TA)]*exp(-UL/MCE)$$

where TP is the plate temperature for the current hour, TPP the plate temperature for the previous hour, S, UL, TA as previously indicated, and MCE is the effective heat capacity of the collector, calculated as outlined by Duffie and Beckman [6] for the 1, 2, and 3 cover collectors to be 6.6, 10.7, and 15.2 kJ/(sq m-K).

Storage Model

In this study water with a specific heat of 4.189 kJ/(kg-K) is used as both the heat transfer fluid and the storage medium. As shown in Lof and Tybout's [16] study on solar space heating, the optimum mass of storage is in the range of 50 to 75 kg per square meter of collector, with variations in this range having a relatively small effect on the cost of delivered energy or the fraction of heat load carried by the solar system. The mass of storage here is fixed at 61 kg of water per square meter of collector as suggested by Butz, et al. [4]. Beckman, et al. [3] show that modeling stratification effects in water storage produces results only 1 to 3% different from modeling an unstratified system, so the system modeled here uses an unstratified model for storage.

The storage vessel is a cylindrical water tank taken to have a height to diameter ratio of 3:1 and insulation with a heat transmission coefficient of 1.44 kJ/(sq m-hr-K) [6]. The size and surface area are determined in the program from the mass of storage water and the assumptions of a constant density of 1000 kg per cubic meter and the height to diameter ratio of 3:1. Thermal losses from storage are then determined from the area U-value product, the storage temperature, and the room temperature.

A schematic of the solar collector and storage system illustrating the mode of operation is presented in Figure 4. Energy is transferred from storage to incoming water from the main for hot water use by means of a heating coil located within the solar system storage tank, and from storage to the house by means of a water to air heat exchanger. The size and heat transfer characteristics of the heat exchanger are not specifically modeled, but it is assumed as suggested in reference 3, that the water and air flow rates are modulated so that the average rate of energy transfer across the load heat exchanger is equal to the average rate of energy required by the heating load. Thus the heat exchanger effects may be neglected.

For the system described above, an energy balance on the fully mixed storage tank is given by .

$$M*Cps*dTs/d\tau = QU - QL - QSHW - QTL \qquad (18)$$

M, Cps = mass, specific heat of storage, kg, kJ/(kg-K)

Ts = storage temperature, K

τ = time, h

QU = rate of transfer of energy to storage, kJ/h
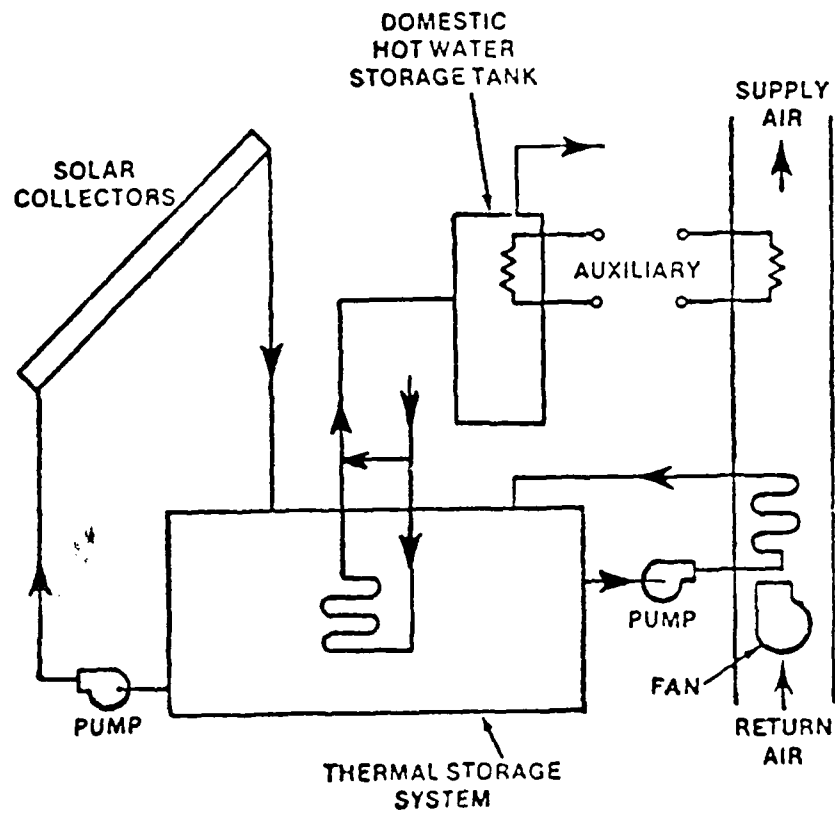
Figure 4.   Solar system schematic.

QL = rate of transfer of energy to space heat load, kJ/h

QSHW = rate of transfer of energy to hot water load, kJ/h

QTL = rate of heat loss from storage, kJ/hr, given by
$$QTL = Us*As*(Ts-Tr)$$

Us, As = heat transfer coefficient and area of storage tank

Ts, Tr = storage tank and room temperatures, K

As indicated by Duffie and Beckman [6], equation 18 may be integrated in one hour time steps by Euler integration to determine the storage tank temperature at the end of the hour from the temperature at the beginning of the hour and the known energy inputs and outputs. The expression is solved hourly in the simulation for the storage temperature, which has an upper limit of 90 degrees C. When the useful energy collected raises the storage temperature above this maximum, the storage temperature is set equal to the maximum value and the amount of excess energy, which is assumed dumped to the atmosphere, tabulated. The simulation thus assumes a controller which senses the storage temperature and halts the collector pump when the maximum temperature is reached. As indicated in reference 3, the minimum storage temperature at which the water to air heat exchanger is effective is on the order of 26-30 degrees C. A temperature of 29 degrees C was used here as the storage temperature below which delivery of energy from storage to the loads is halted and auxiliary energy used for both space and hot water. Thus, for space heating, either all or none of the energy requirements are met from storage in any given hour, based upon the calculated storage temperature for that hour. The solar system storage acts as a preheater for water from the mains when the storage

temperature is below the required hot water value of 60 degrees C.
If the storage temperature is above 60 degrees, a control system and
a mixing valve, not specifically modeled, are assumed to operate to
mix water from the mains with water heated by the storage system to
deliver 60 degree C water to the domestic hot water tank. Thus, for
domestic hot water, auxiliary energy is used exclusively if the stor-
age temperature is below the minimum storage temperature, is used to
increase the domestic hot water temperature to the required value of
60 degrees if the storage temperature is above minimum but below 60
degrees, and is not required if the storage temperature is above 60
degrees.

With the known requirements for space heat and hot water,
the solar energy input, and the simulation of the collector and stor-
age system as outlined above, the annual requirements for auxiliary
energy can be determined and used to find the most economic mix of
conventional and solar energy. This economic optimization of the so-
lar system size is discussed in the next chapter.

CHAPTER VI

COST OPTIMIZATION OF COLLECTOR AREA

Introduction

The preceding chapters have outlined the methods of model-
ing the thermal performance of the components used in the solar sys-
tem simulation and have not dealt with questions of cost. However,
the decision to incorporate solar energy for the heating of a resi-
dence and the selection of the size of the system, assuming the in-
dividual thinks rationally, is an economic one. This chapter will
present the methodology used to determine the optimum size of the so-
lar system from the results of the thermal performance simulation of
the house and solar system.

As previously indicated in Chapter I, studies by Löf and
Tybout [15, 16] have clearly shown that designing a solar system to
provide 100% of the heating requirements for a conventionally con-
structed residence is not feasible. The size of the collector array
and storage system required raise the cost far above the cost of con-
ventional energy sources and produce architecturally undesirable con-
sequences [1], such as the inability to incorporate the solar system
into the construction of the residence. Consequently, a conventional
system capable of meeting the worst case heating requirements of the

building must be part of the residence and its costs are required whether or not a solar system is included. The only savings then offered by solar energy, where it is of low enough cost, is in the reduction of the cost required for fuel for the conventional heating system. Thus, as demonstrated by Duffie, Beckman, and Klein in reference 3, the conventional system cost can be considered as a base cost common to both systems and the cost analysis carried out as a comparison of the costs above base.

In a similar manner, the cost of insulation was included in this study as a cost above base by assuming that a decision regarding the level of insulation is made concurrently with the decision regarding the solar system. Type II insulation, representing a moderately insulated house, is taken as the base level. The cost of increasing the insulation to Type III, or the savings from deciding to insulate only to the level of Type I are calculated and included in the cost analysis. In addition, it is assumed here that the solar system is well designed and has negligible maintenance and pumping costs.

Annual Energy Cost

The annual cost of energy with the mix of solar and conventional systems, under the assumptions listed above, may be expressed as:

$$EUAC = (SOLCS + CSTI)*I + CSTA \qquad (19)$$

EUAC = uniform annual cost of energy for space and hot water, dollars per year

SOLCS = total capital cost of solar system, dollars

CSTI = total capital cost of insulation, above or below base, dollars

I = capital recovery factor for assumed interest rate and time period, fraction per year

CSTA = uniform annual cost of auxiliary energy, where auxiliary energy refers to the energy provided by the conventional heating system.

Solar System Cost

The total capital cost of the solar system is the sum of the costs for the collector, piping, pumps, controls, and storage minus the tax incentive provided under current law for installation of a solar system. A cost of $100 per square meter for a two cover collector was taken as a base collector cost [18], with an additional cost or savings of $8.60 for a three cover and one cover collector, respectively. As indicated in the study by Butz, et al. [4], the cost of storage can be considered a linear function of collector area and their figure of $8/sq m for the cost of the storage vessel, water, and insulation was used here. The additional solar system costs for piping, pumps, and controls, as suggested in reference 3, were set at $375, independent of collector area. Current tax policy [25] provides that of the total cost of a solar installation, 30% of the first $2000 and 20% of the remaining cost, up to a maximum of $10000, are rebated to the purchaser as tax credit. Under these assumptions, the initial capital cost of the solar system is

$$CCOST = (\$100 + \$8.6*(N-2) + \$8)*AC + \$375$$

where N is the number of collector covers and AC is the collector area. The tax savings is then

$$
TAXSV = \begin{cases} 0.3*CCOST & , & CCOST<\$2000 \\ \$600 + 0.2*(CCOST-\$2000), & \$2000<CCOST<\$10000 \\ \$2200 & , & CCOST>\$10000 \end{cases}
$$

The final capital cost of the solar system is then

$$
SOLCS = CCOST - TAXSV
$$

Insulation Cost

As indicated previously, the cost of insulation, CSTI, was treated as a cost above or below the base cost of insulating the residence to insulation Type II. The cost of fibrous insulation used for the wall and ceiling insulation in the residences considered here was taken from the February 1980 ASHRAE Journal [13] as $0.08 per sq ft (0.0929 sq m) for the first inch (2.54 cm) and $0.05 per sq ft for each additional inch of insulation. These costs, the total wall and ceiling area, and the difference in insulation thickness from Type II insulation were then used to calculate the total cost or savings above or below base for each insulation type for each house size considered. Table 1 summarizes the results obtained. The capital recovery factor, I, used to convert the total capital costs to a uniform annual cost was 0.11746 [8] for the assumed 20 year amortization period at an interest rate of 10%.

Auxiliary Energy Cost

The cost of auxiliary energy is determined from the amount of auxiliary energy required and the unit cost of the fuel used. An initial cost of $6 per million kJ, at the upper range of values considered by Butz, et al. in their 1974 study, was used. It was not,

HOUSE SIZE

	I	II	III
I	- $263	- $373	- $491
II	$0	$0	$0
III	$717	$1021	$1346

INSULATION TYPE

Table 1 . Capital cost of insulation above or below insulation Type II. Negative values are savings, positive values increased cost.

however, held constant over the 20 year period considered in each sim-
ulation. A Westinghouse study prepared for the Department of Energy
[28] indicates that conventional energy costs will increase at about
8% per year through the year 2000, and this factor was taken into
account in order to make an equitable comparison between the uniform
annual cost of the solar system and the annual cost of auxiliary
energy over the 20 year period. This was accomplished by assuming the
value of required auxiliary energy obtained from the simulation using
the average year represents the average annual value over the 20 year
period. Using the figure of $6 per million kJ as an initial cost,
the total cost of auxiliary energy for the 20 year period was calculat-
ed and converted to an equivalent uniform annual cost by the use of a
capital recovery factor (0.10185) at 8% for 20 years.

Summary

Under the assumptions listed above, equation 19 can be seen
to represent the total annual cost above base for delivered energy
for space and hot water heating from the solar and conventional systems
as a function of collector area. Figure 5 illustrates the relative
contributions of the two terms in the equation with increasing collec-
tor area. As the collector area increases, collector costs (for a
fixed insulation cost) increase linearly. However, as annual solar
system efficiency decreases with increasing collector size, less and
less auxiliary energy is replaced by a unit increase in collector area
because the solar system does not operate at full capacity on a year
round basis. The result is a minimum on the curve depicting the total
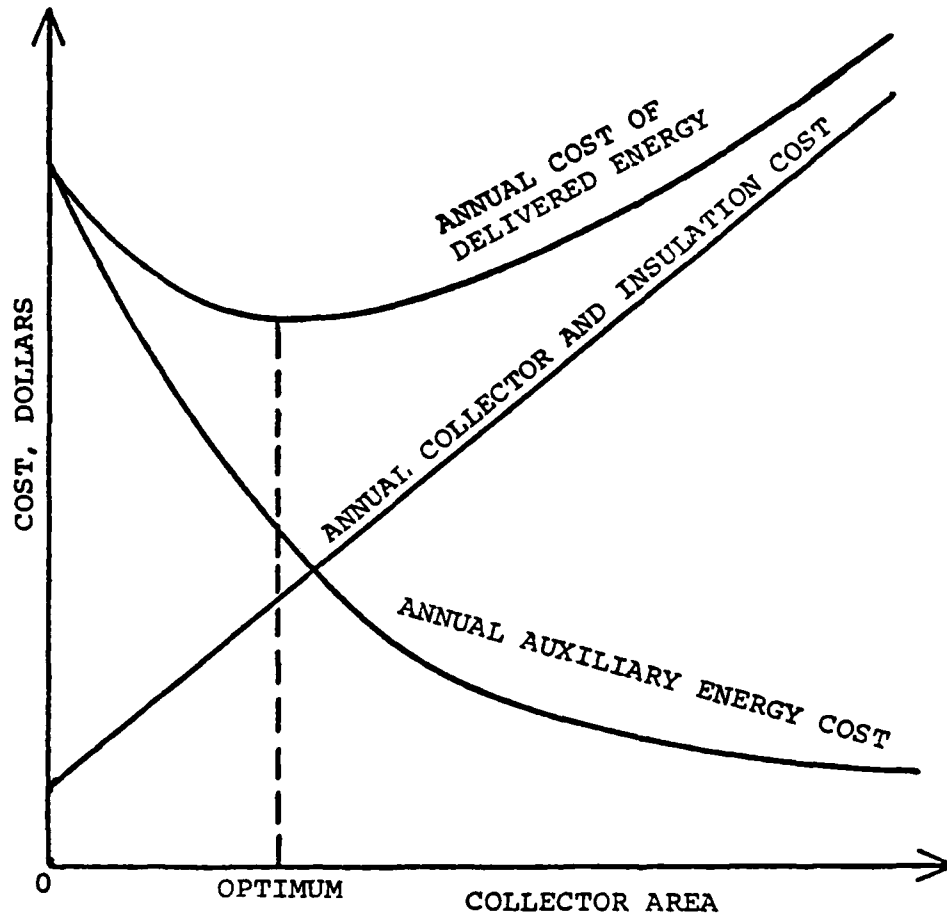
Figure 5.   Relative contributions of collector and insulation and auxiliary energy to cost of delivered energy for space and hot water heating.

annual cost of energy which occurs at the optimum collector size. Optimum in this case refers to the collector size which produces the lowest annual energy cost for space and hot water heating from the mix of solar and conventional energy sources.

This method of economic analysis, coupled with the thermal analyses of solar system performance and building heat loss as out-lined in previous chapters, forms the basis for comparison of the effect of the two methods of modeling heat loss on the selection of optimum collector size. The results are presented in the next chapter.

CHAPTER VII

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

Results

The procedures outlined in previous chapters were used to
develop a numerical model for the simulation of building heat loss
and solar system performance. The program, listed in Appendix C,
uses the Oklahoma City average year discussed in Chapter I for hourly
simulation of the building heat loss and solar system performance
using Model I and Model II methods. It determines the amount of aux-
iliary energy required, the percentage of the heating requirements
provided by the solar system, and the annual cost of energy for space
and hot water heating. A total of 172 simulation runs for various
combinations of house size, insulation type, and number of collector
covers and collector area were accomplished and are summarized in
Tables B-1 to B-27 in Appendix B.

Each table in Appendix B presents a comparison of the simu-
lation results for collector areas up to 100 square meters for a given
house size, insulation type, and number of collector covers. Table 2
is an example of the information contained in each table in Appendix
B. The first column, labeled AC, gives the collector size in square
meters for which the comparison between Model I and Model II results

43

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$963	22.7	58.4	.414	$237	$1995 − 599 $1396	65.4
	II	$947	23.5	61.1	.378	$253		64.1
30	I	$878	45.6	70.3	.354	$318	$3615 − 923 $2692	46.0
	II	$859	47.2	72.5	.326	$342		44.4
45	I	$850	64.2	76.8	.328	$343	$5235 −1247 $3988	31.3
	II	$835	65.1	79.5	.284	$365		30.0
60	I	$870	77.8	81.8	.308	$318	$6855 −1571 $5284	20.4
	II	$865	77.8	83.8	.261	$333		20.0
75	I	$929	87.2	85.6	.291	$256	$8475 −1895 $6580	12.7
	II	$925	87.4	87.3	.244	$270		12.5
100	I	$1118	95.7	91.0	.268	$60	$11175 − 2200 $ 8975	5.2
	II	$1116	96.4	92.2	.223	$71		5.1

Table 2.   Example of tables contained in Appendix B.   This table summarizes the simulation results for house size III, insulation type II, 2 cover collector.

is made. The next column lists the uniform annual cost of energy for
space and hot water requirements (EUAC, equation 19) obtained using
each model for that collector size. In the next two columns, the
percentage of the total annual energy requirement for space heat and
hot water provided by the solar system are listed for each model.
Next is the annual efficiency of the solar system, defined as the
total amount of useful energy provided by the solar system divided by
the annual amount of energy incident upon the collector array. The
column labeled Annual Savings gives the dollar value of the annual
energy saved by the solar system for the given collector area above
that given by the use of conventional fuel alone for space and hot
water heating. Under the heading Solar System Cost, the figures rep-
resent the initial capital cost of the solar system, minus the tax
credit provided, and the resulting figure for the final capital cost
of the solar system (SOLCS, equation 19). Finally, the last column
presents the annual amount of auxiliary energy which the simulation
produces for each heat loss model in millions of kilojoules.

It is apparent, upon reviewing the results given in these
tables, that the same optimum collector area (as defined in Chapter
VI) would be selected for each building heat loss model with a given
house size, insulation level, and number of collector covers. The
results from Model II indicate a slightly lower annual energy cost
and amount of auxiliary energy and a slightly higher annual savings
than the Model I results, though the difference is generally less
than 5%. Model II results also show a slightly greater percentage of
the space and hot water heating loads carried by the solar system

than indicated by Model I results, but the annual system efficiency for Model II is lower than with Model I, a point which will be discussed in more detail later. It is also clear that regardless of the heat loss model used or the size of the house and solar system, a two cover collector is always significantly more cost effective than one cover and slightly more cost effective than three covers, a result which Löf and Tybout found to be true in their study of solar space heating [15]. Finally, recalling that the figure given for the annual cost of energy includes the cost of insulation above or below base, the results show that both models predict that the highest insulation level provides the least cost of energy for space and hot water heating.

These results are summarized in Figures 6, 7, and 8, which present plots of the annual cost of energy for space and hot water heating as a function of collector area for house sizes I, II, and III, respectively. The label on the cost curves in each plot indicate the insulation level, I, II, or III and the number of collector covers, 1 or 2. Since the values for both heat loss models resulted in nearly identical plot curves, for clarity the curves for Model II only are presented. Similarly, the values for a 3 cover collector were nearly coincident with the two cover values in each case and were not plotted. These figures clearly demonstrate the cost effectiveness of increased insulation for each house size, and the superiority of the two cover collector over the one cover collector.

Figures 9, 10, and 11 are presented as an example of the daily performance of the two models of heat loss and the influence by
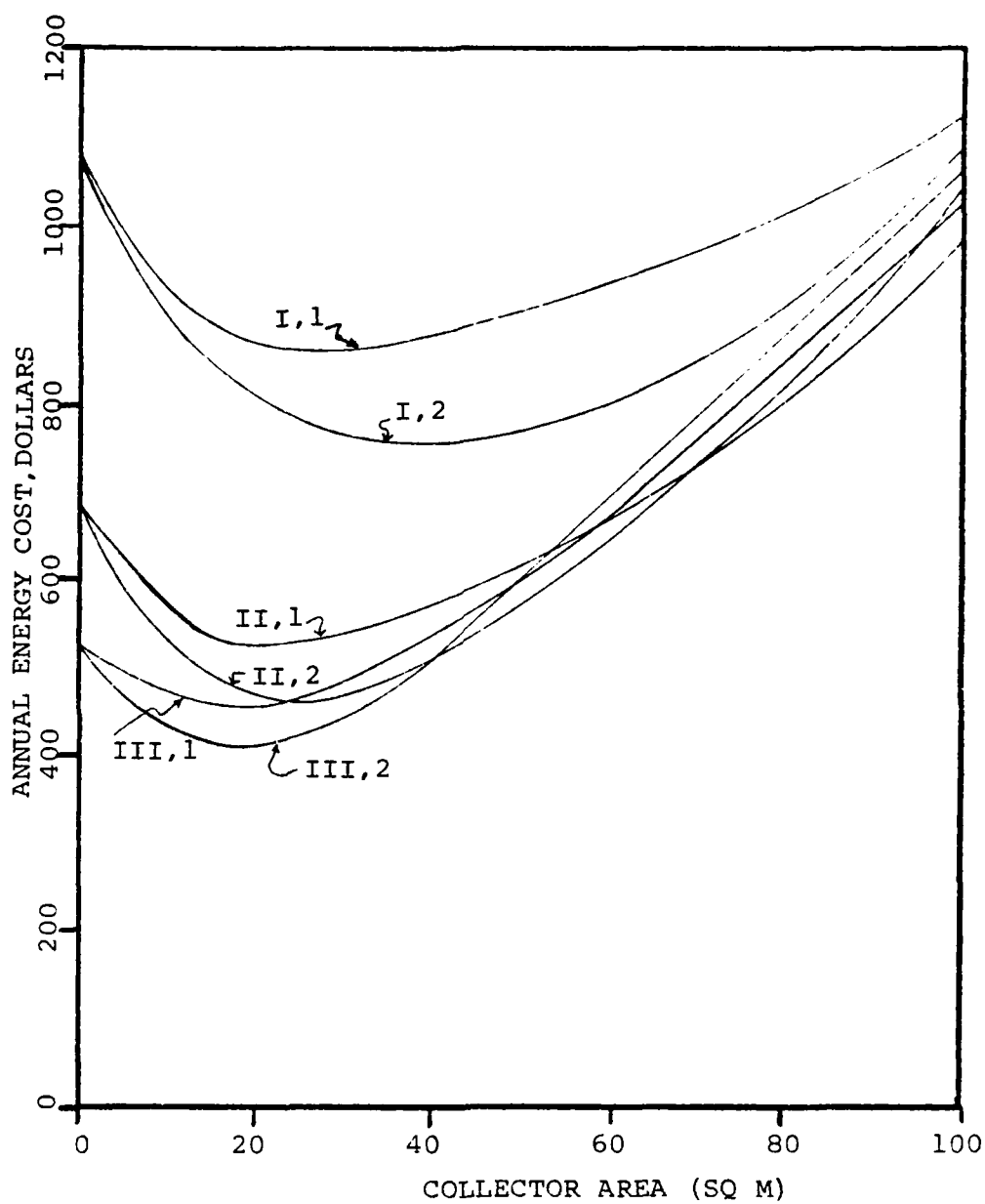
Figure 6. Annual cost of delivered energy for
space and hot water heating for house size I for
3 insulation levels and 1 or 2 collector covers.
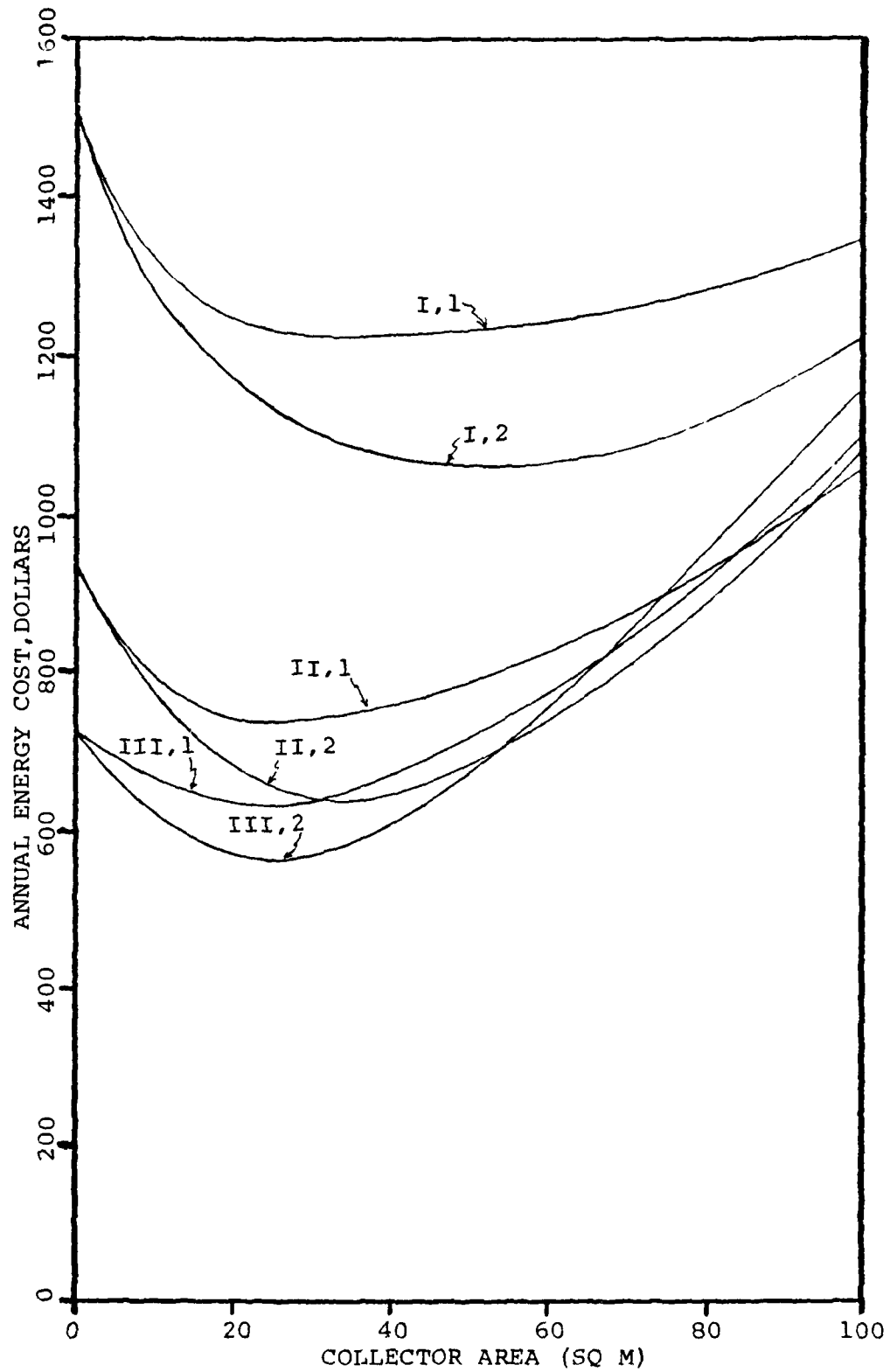
Figure 7. Annual cost of delivered energy for
space and hot water heating for house size II for
3 insulation levels and 1 or 2 collector covers.
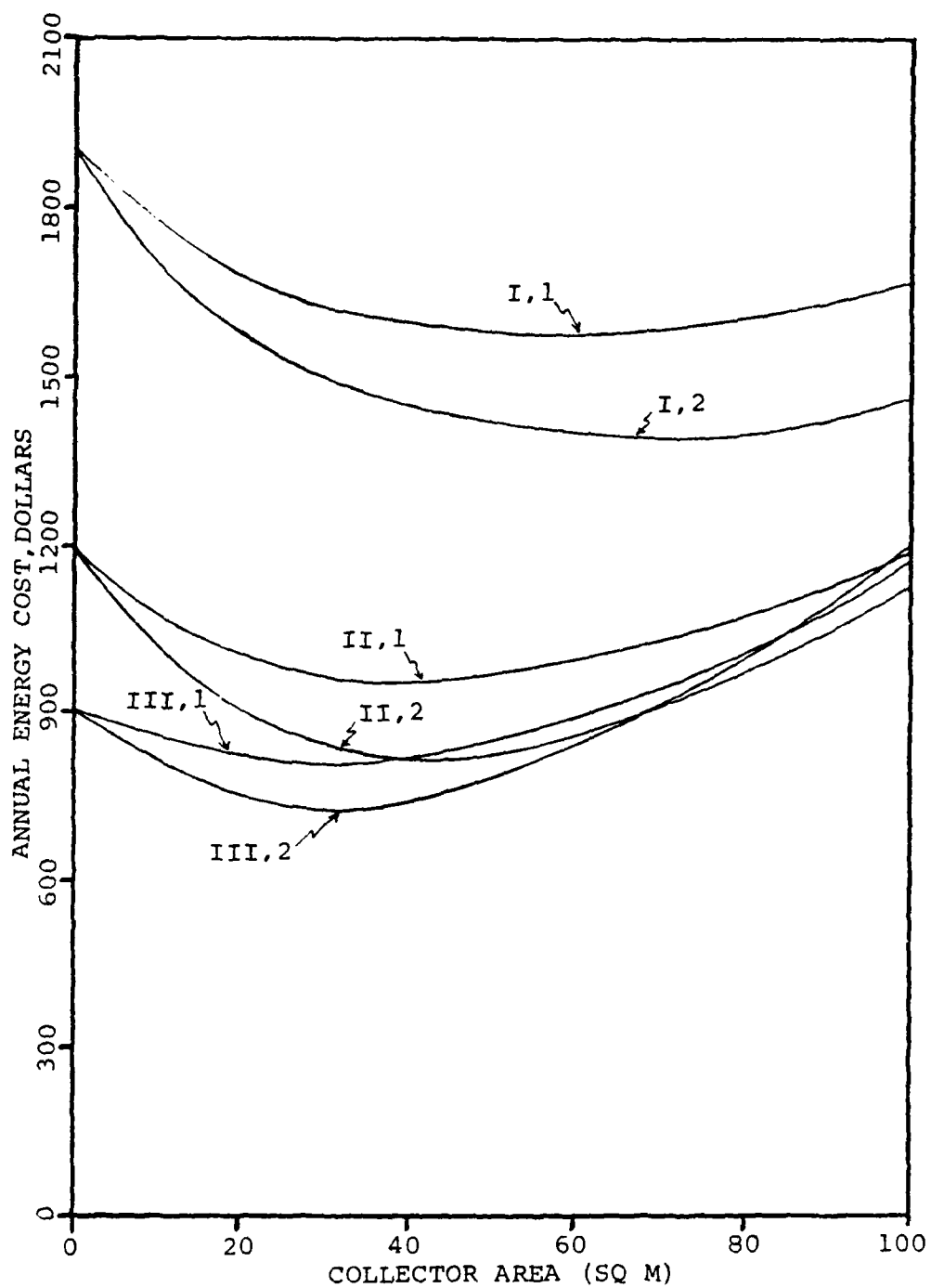
Figure 8. Annual cost of delivered energy for
space and hot water heating for house size III for
3 insulation levels and 1 or 2 collector covers.
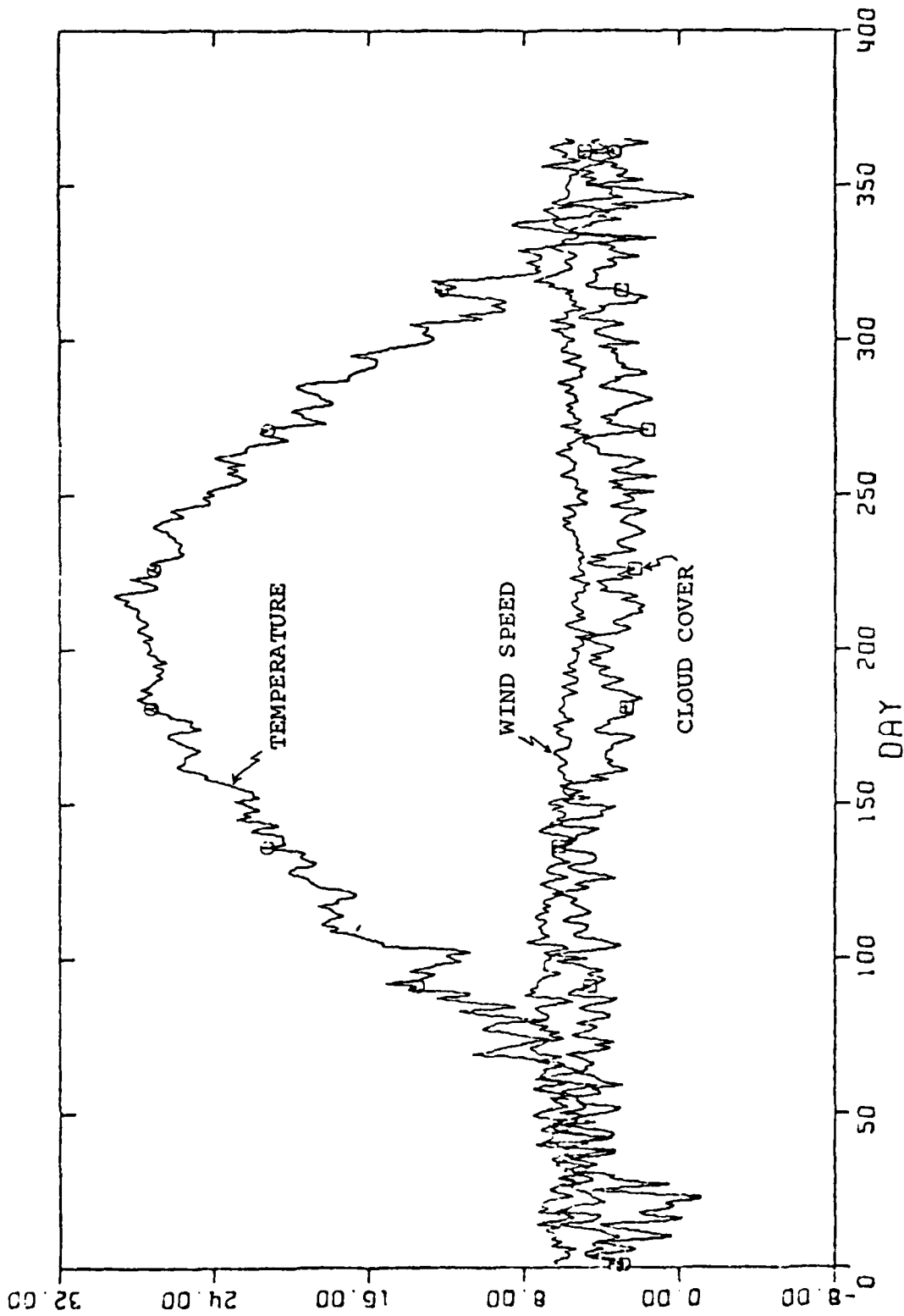
Figure 9. Daily average value of temperature in degrees C, wind speed in meters per second, and cloud cover in tenths, for Oklahoma City, Oklahoma.
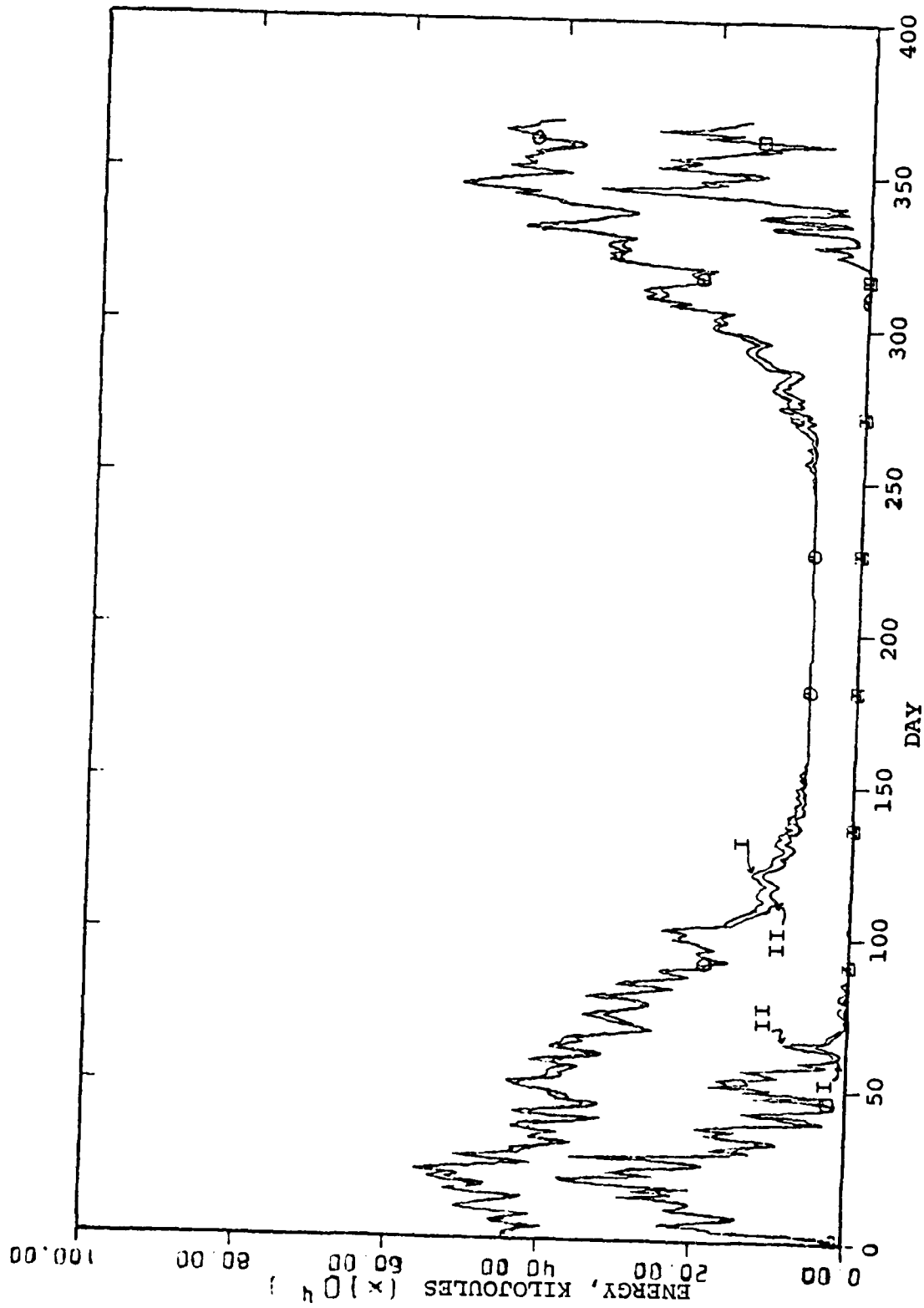
Figure 10. Daily average values of building heat requirements and auxiliary energy for Model I and Model II heat loss models.
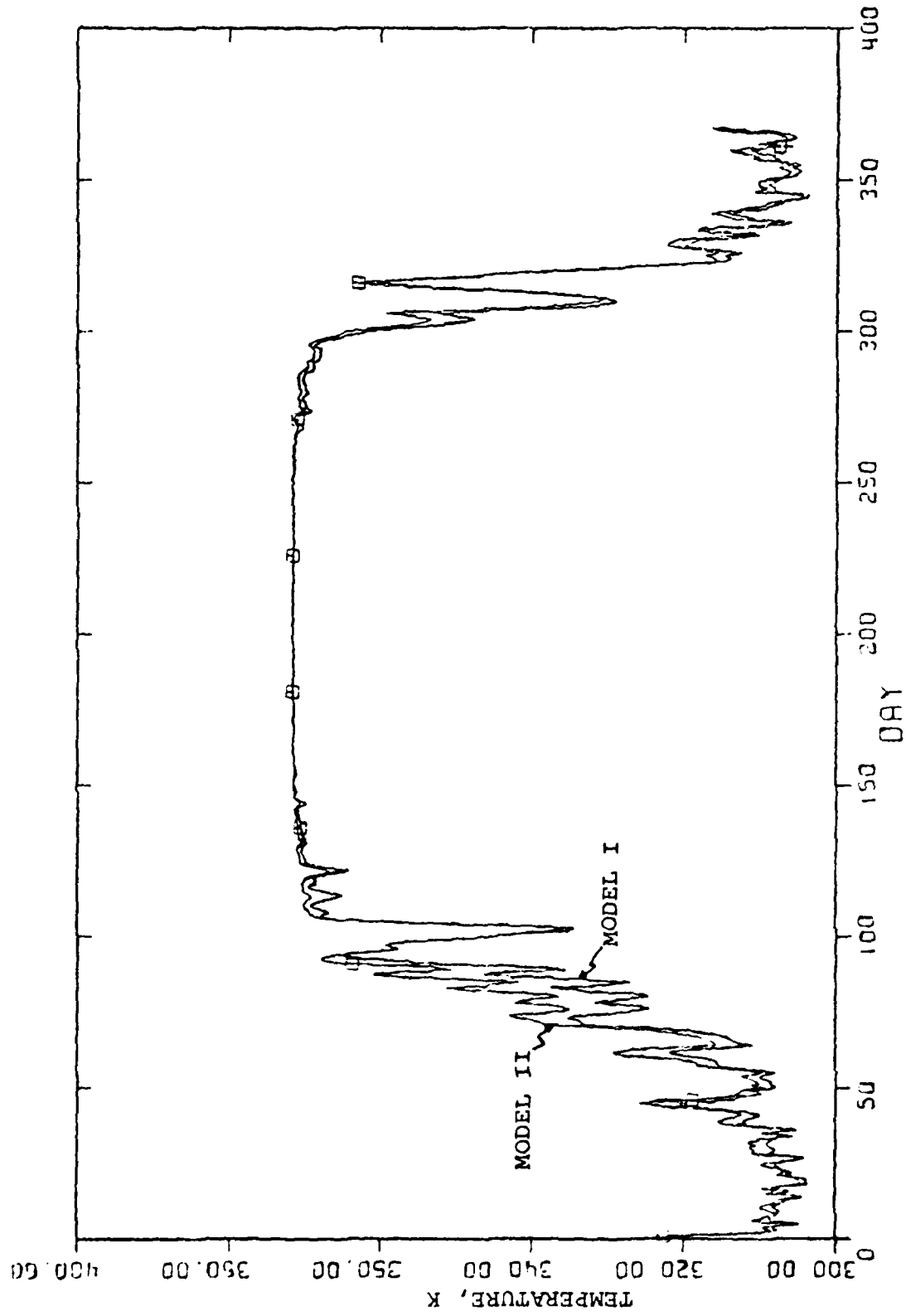
Figure 11. Daily average solar system storage temperature.

each on the solar system performance. They were obtained with house

size II, insulation type II, a two cover collector, and 36 square

meters of collector. Figure 9 shows the daily average value of tem-

perature in degrees C, the daily average wind speed in meters per

second, and the daily average cloud cover in tenths. In Figure 10,

the upper two plots are the daily average values of building heat

requirements for space and hot water and the lower two plots are the

daily average values of auxiliary energy, labeled for I for Model I

and II for Model II. The values of building heat required and auxil-

iary energy are nearly coincident for both models, with the greatest

departures in the spring and fall when the building space heat demand

is at a low level. Figure 11 shows the daily average storage tempera-

tures for both models. It indicates that the storage temperature with

Model II is generally higher than with Model I. The lower annual so-

lar system efficiency referred to earlier is a direct consequence of

this higher storage temperature, since the collector losses are great-

er and the useful energy collected lower with a higher fluid inlet

temperature to the collector.

A more detailed picture is given in Figures 12, 13, 14, and

15 where a 48 hour period of the hourly simulation for each model is

shown for the same house and solar system. Figure 12 is an hourly

plot of the same weather parameters as given in Figure 9. In Figure

13, the hourly heat requirements using Model I and Model II are pre-

sented, along with the auxiliary energy required for both models and

the solar gain through the building windows for Model II. The Model

II values of heat loss are greater than Model I at night and in the

53
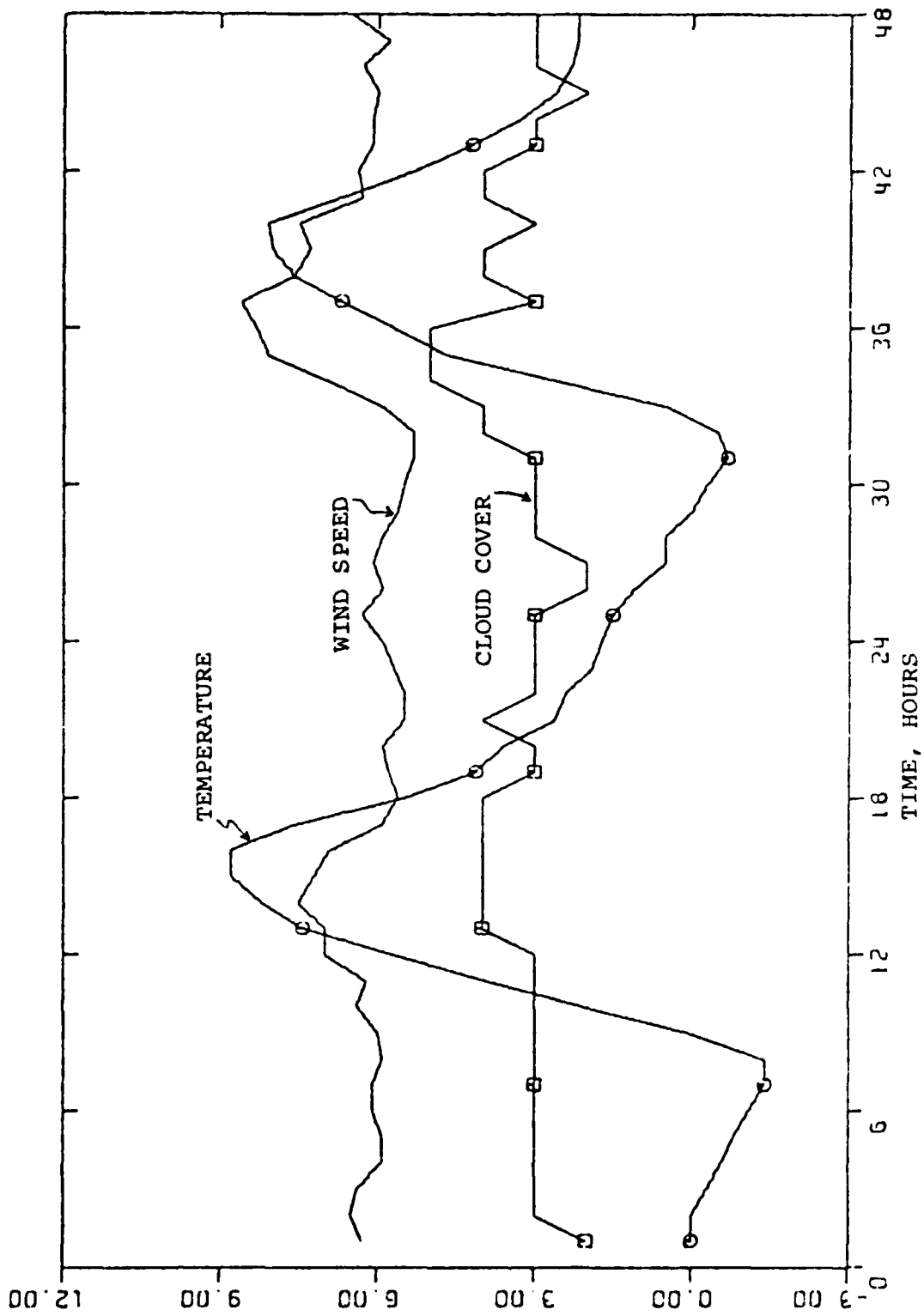
Figure 12. Hourly values of temperature in degrees C, wind speed in meters per second, and cloud cover in tenths.
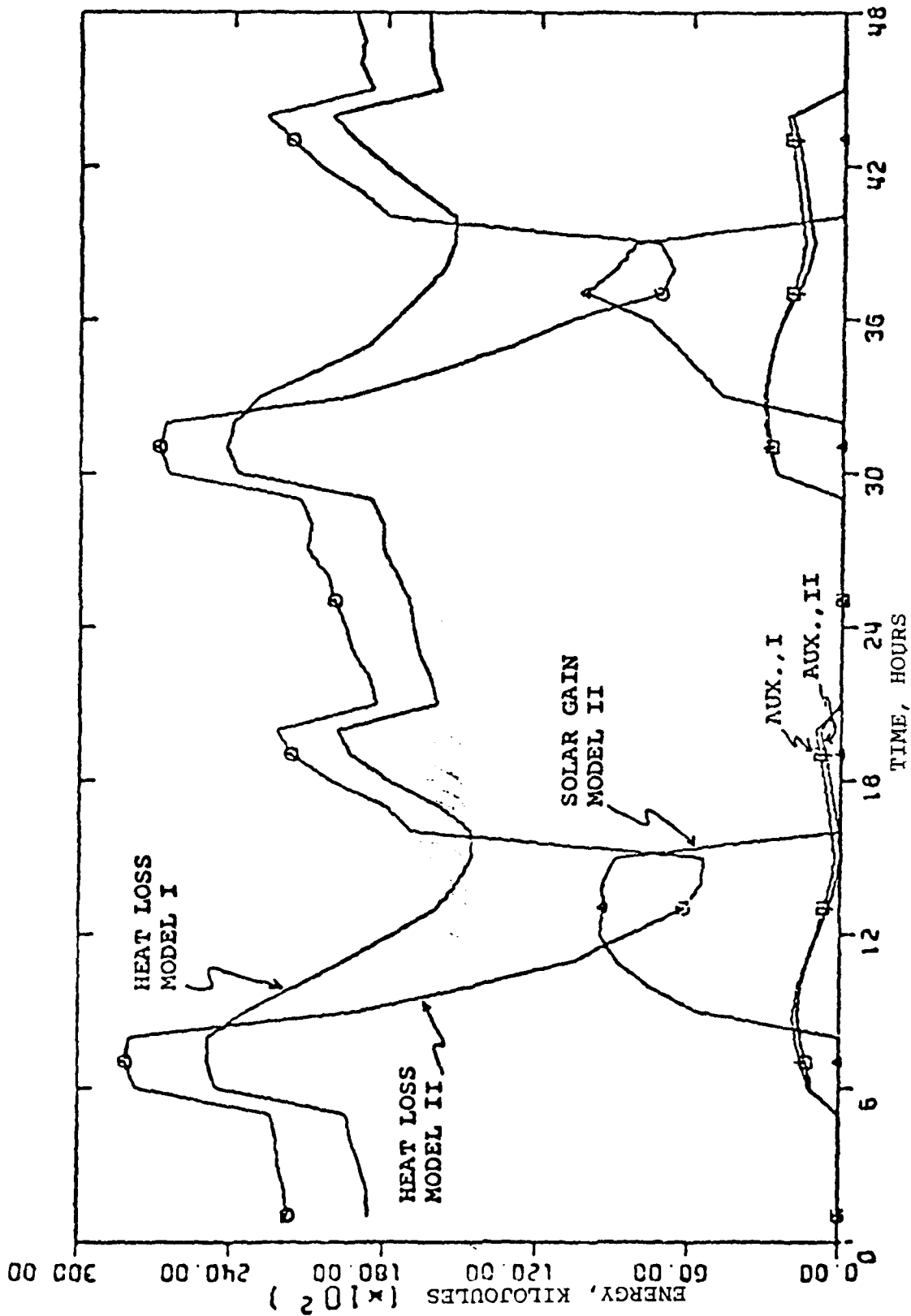
Figure 13. Hourly values of building heat requirements and auxiliary energy for heat loss models I and II and useful solar gain for model II.
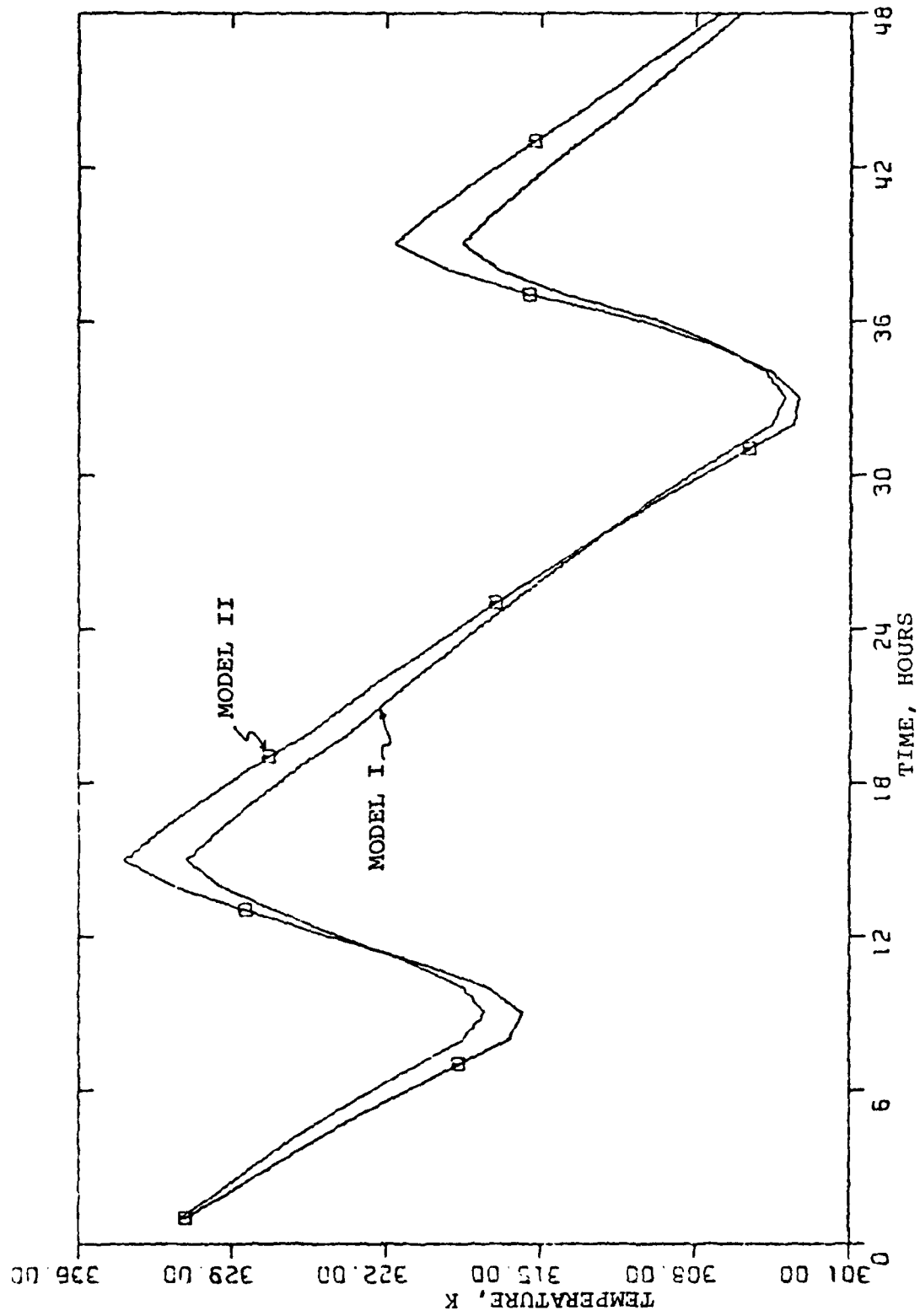
Figure 14. Hourly solar system storage temperature with heat loss models I and II.
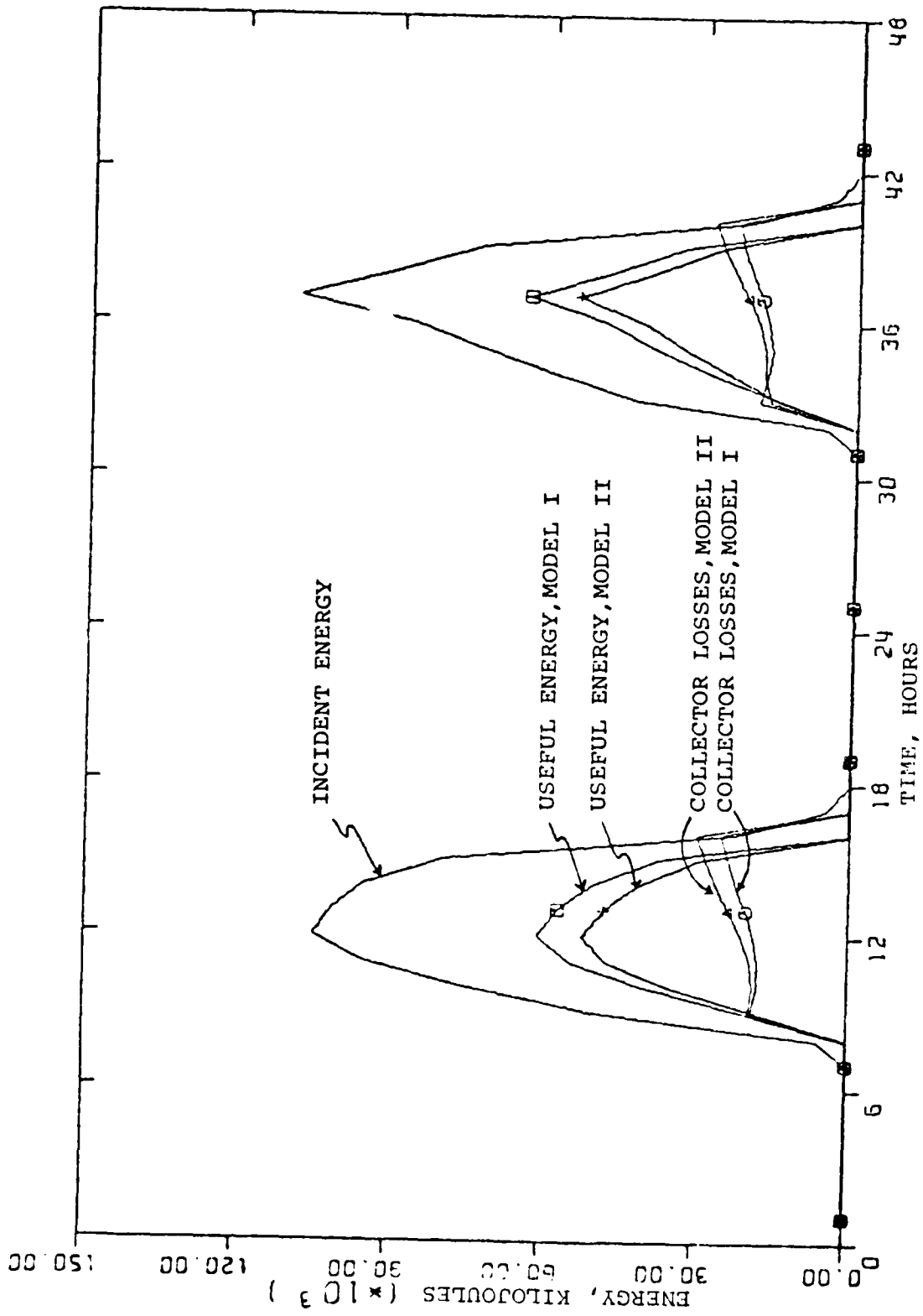
Figure 15. Solar collector performance with heat loss models I and II.

early morning, but are significantly reduced below the Model I values by the solar gain during the day. The effect on the storage temperature and efficiency of the solar system is apparent in Figures 14 and 15. As seen in Figure 14, the storage temperature with Model II falls below the value given by Model I at night and rises above the value given by Model I during the day when solar energy collection and input to storage takes place. The effect of the solar system efficiency can be seen in Figure 15 where the total energy incident on the collector, the useful energy collected, and the collector losses are plotted for each heat loss model. With the same value of incident energy on both collectors, the collector losses with Model II exceed those with Model I because of the higher fluid inlet temperature. Consequently, less useful energy is collected and the system efficiency is lower.

Conclusions

These results show that the time distribution of heating demand as simulated by heat loss Model II does result in a significant difference in solar system performance on a short term basis from the results given by Model I. However, in contrast to the results found by Gutierrez, et al. [9] for domestic hot water only, these short term differences between the two models do not result in significantly different long term fractions of the load carried by the solar system. Indeed, it is the departure in the time distribution of the heat load given by Model II from that of Model I which produces a lower annual efficiency and results in the selection of

the same optimum collector size for both approaches even though the Model II approach gives lower annual auxiliary requirements. Thus, the Model II approach, though more complex and requiring much more computer time, does not produce different results in the selection of the solar system size at Oklahoma City. This indicates that where the purpose is the simulation of long term average results for the selection of the size of the solar system, the increased complexity and cost of the Model II approach are not worthwhile. On the other hand, if the purpose is the simulation of the short term performance characteristics of a solar system, these results indicate that a higher level approach than that of Model I is necessary.

Recommendations for Further Research

1. This analysis was accomplished at a single station. SOLMET data tapes are available for locations with significantly different climate regimes and could be used to determine whether different climates would produce different results.

2. The building models used were of conventional construction characteristics. An extension of the analysis to houses designed to be solar residences could be accomplished. This could include an analysis of the effect of varying the size and location of the building windows in a conventionally constructed residence.

3. Each house considered here was a south facing structure with the collector optimally tilted for space heating. The program is written to accept off-south orientations and any collector tilt angle and could be used to study the differences between the optimum south facing system and other orientations.

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APPENDIX A

HOUSE DESIGN AND INSULATION CHARACTERISTICS

63

Table A-1. House Design Data

| | House Size | | |
	I	II	III
Area	92.9 sq m	134.8 sq m	180.0 sq m
Configuration	7.62 x 12.2 m	9.5 x 14.3 m	12.0 x 15.0 m
Foundation Length	39.6 m	47.5 m	54.0 m
Window Area	9.7 sq m	13.5 sq m	17.7 sq m

Table A-2. House Construction Data

| | Insulation Type | | |
	I	II	III
Roof	tile shingles building paper on wood sheathing	tile shingles building paper on wood sheathing	asphalt shingles on wood sheathing
Attic-Walls	lapped wood siding wood sheathing	brick veneer wood sheathing	brick veneer wood sheathing 1 in insulation board
Ceiling	3/8 in gypsum 1/2 in plaster 1 in fibrous insul	3/8 in gypsum 1/2 in plaster 3 in fibrous insul	3/8 in gypsum 1/2 in plaster 12 in fibrous insul
Walls	gypsum lath 4 in air space building paper wood sheathing lapped wood siding	gypsum lath 3 in air space 1 in fibrous insul building paper wood sheathing 4 in face brick	gypsum lath 1 in air space 3 in fibrous insul building paper wood sheathing 8 in common brick
Glass	single pane aluminum sash	double pane wood sash	double pane wood sash storm sash in winter
Doors	standard 1 in exposed	standard 1 1/2 in storm door	2 in insulated storm door
Basement	below grade concrete uninsulated walls	below grade concrete 1 in wall insul	below grade concrete 2 in wall insul

Table A-3. Heat Transmission Coefficients, kJ/(sq m-h-C)

	Insulation Type		
	I	II	III
Roof	12.4	12.4	10.0
Attic Walls	8.9	8.9	5.9
Ceiling	3.9	1.6	0.9
Walls	5.1	2.8	1.5
Glass	25.4	10.7	9.8
Doors	7.6	6.5	5.7
Basement	7.2	2.8	2.2

Table A-4. Coefficients for Peterson's Infiltration Equation

Insulation	Coefficient		
Type	A	B	C
I	0.10	0.216	0.0300
II	0.10	0.0162	0.0225
III	0.10	0.0108	0.0150

APPENDIX B

SUMMARY OF SIMULATION RESULTS

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$975	9.9	47.5	.357	$121	$1270 - 381 $ 889	73.4
	II	$933	11.5	49.2	.306	$136		70.0
18	I	$908	23.3	56.3	.278	$186	$2164 - 633 $1531	61.8
	II	$886	25.1	58.3	.267	$192		60.0
27	I	$890	33.6	60.2	.248	$202	$3059 - 81i $2248	53.4
	II	$873	35.9	63.9	.236	$211		52.1
36	I	$883	43.1	65.0	.229	$208	$3953 - 991 $2962	46.0
	II	$880	44.6	67.8	.209	$210		45.7
50	I	$901	55.1	67.7	.202	$188	$5345 -1269 $4076	36.7
	II	$898	56.7	68.3	.183	$196		36.5
75	I	$982	71.6	75.0	.161	$103	$7830 -1766 $6064	24.3
	II	$980	72.3	77.0	.151	$113		24.1
100	I	$1118	83.1	80.0	.131	$ 0	$10315 - 2200 $ 8115	15.7
	II	$1115	83.3	80.7	.130	$ 0		15.1

Table B-1. Summary of simulation results for house size I, insulation type I, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$937	13.6	52.5	.433	$158	$1347 – 404 $ 942	69.8
	II	$893	15.6	54.7	.396	$176		66.2
18	I	$847	30.6	63.9	.375	$247	$2319 – 664 $1655	55.6
	II	$819	32.5	64.5	.354	$259		53.3
27	I	$810	43.8	69.8	.351	$281	$3291 – 858 $2433	45.1
	II	$781	46.1	71.4	.324	$301		42.8
36	I	$788	55.7	74.3	.335	$301	$4263 –1053 $3210	35.8
	II	$761	58.0	76.7	.297	$324		33.6
50	I	$791	70.5	79.6	.315	$294	$5775 –1355 $4420	24.4
	II	$772	72.1	81.7	.267	$315		22.9
75	I	$879	88.0	86.2	.287	$198	$8475 –1895 $6580	10.9
	II	$871	88.7	87.8	.240	$215		10.2
100	I	$1074	96.8	91.6	.264	$ 0	$11175 – 2200 $ 8975	3.8
	II	$1073	96.7	92.8	.220	$ 0		3.7

Table B-2.   Summary of simulation results for house size I, insulation type I, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$943	13.7	52.6	.459	$152	$1424 - 427 $ 997	69.7
9	II	$895	15.7	55.6	.414	$173		65.9
18	I	$857	30.9	64.2	.430	$235	$2474 - 695 $1779	55.5
18	II	$820	33.2	67.0	.388	$257		52.2
27	I	$817	45.2	70.7	.417	$273	$3523 - 905 $2618	43.9
27	II	$781	48.0	74.0	.370	$301		41.7
36	I	$793	58.1	75.8	.408	$295	$4573 -1115 $3458	33.8
36	II	$767	60.4	78.5	.360	$318		31.6
50	I	$802	73.4	81.3	.394	$281	$6205 -1441 $4764	22.0
50	II	$786	74.8	83.8	.346	$300		20.7
75	I	$907	91.2	88.9	.373	$167	$9120 -2024 $7096	8.2
75	II	$900	91.6	90.9	.327	$183		7.5
100	I	$1149	98.9	94.9	.356	$ 0	$12035 - 2200 $ 9835	1.9
100	II	$1148	98.9	95.3	.314	$ 0		1.8

Table B-3. Summary of simulation results for house size I, insulation type I, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$586	17.6	51.9	.350	$98	$1270 − 381 $ 889	39.3
	II	$563	19.6	54.7	.300	$112		37.5
18	I	$540	37.6	64.3	.259	$142	$2164 − 633 $1531	29.5
	II	$529	39.6	64.7	.240	$147		28.5
27	I	$540	53.3	69.3	.213	$140	$3059 − 812 $2247	22.6
	II	$534	54.9	70.6	.210	$142		22.1
36	I	$563	65.2	73.9	.187	$116	$3953 − 991 $2962	17.9
	II	$553	67.2	74.3	.184	$122		16.8
50	I	$621	79.2	78.7	.153	$55	$5345 −1269 $4076	11.6
	II	$615	80.1	79.3	.149	$59		11.1
75	I	$779	92.9	84.7	.118	$ 0	$7830 −1766 $6064	5.5
	II	$774	93.3	86.1	.092	$ 0		5.1
100	I	$990	97.7	88.6	.094	$ 0	$10315 − 2200 $ 8115	3.0
	II	$988	97.5	89.8	.063	$ 0		2.9

Table B-4. Summary of simulation results for house size I, insulation type II, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$545	24.3	58.9	.423	$138	$1347 − 404 $ 943	35.6
	II	$526	25.6	61.7	.383	$148		34.0
18	I	$488	49.1	79.3	.354	$193	$2319 − 664 $1655	24.0
	II	$469	51.4	73.5	.326	$205		22.5
27	I	$476	68.5	78.2	.325	$202	$3291 − 858 $2433	15.6
	II	$458	70.5	81.3	.276	$214		14.1
36	I	$494	82.3	83.2	.303	$181	$4263 −1053 $3210	9.6
	II	$484	83.2	85.5	.254	$186		8.8
50	I	$569	94.3	89.3	.277	$100	$5775 −1355 $4420	4.1
	II	$561	94.7	91.6	.227	$104		3.5
75	I	$782	99.9	96.4	.243	$ 0	$8475 −1895 $6580	0.7
	II	$780	99.8	97.5	.200	$0		0.6
100	I	$1056	100.0	99.2	.224	$0	$11175 − 2200 $ 8975	0.1
	II	$1056	100.0	99.3	.189	$0		0.1

Table B-5. Summary of simulation results for house size I, insulation type II, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$550	24.5	59.3	.451	$133	$1424 − 427 $ 997	35.4
	II	$525	26.5	63.1	.407	$149		33.4
18	I	$489	51.3	72.6	.417	$191	$2474 − 695 $1779	22.9
	II	$470	53.2	75.9	.369	$203		21.3
27	I	$482	71.2	80.0	.399	$196	$3523 − 905 $2618	14.3
	II	$466	72.9	82.7	.350	$205		13.0
36	I	$503	85.7	85.3	.385	$170	$4573 −1115 $3458	8.0
	II	$494	86.4	87.6	.337	$175		7.2
50	I	$590	97.2	92.6	.364	$ 77	$6205 −1441 $4764	2.5
	II	$586	97.2	94.0	.318	$78		2.1
75	I	$835	100.0	99.5	.340	$ 0	$9120 −2024 $7096	0.9
	II	$835	100.0	99.5	.300	$ 0		0.9
100	I	$1155	100.0	99.9	.329	$ 0	$12035 − 2200 $ 9835	0.2
	II	$1155	100.0	99.9	.291	$ 0		0.2

Table B-6. Summary of simulation results for house size I, insulation type II, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$502	25.2	55.6	.342	$29	$1270 − 381	26.5
	II	$480	26.7	58.4	.287	$36	$ 889	24.8
18	I	$473	49.9	68.7	.246	$56	$2164 − 633	18.0
	II	$456	53.1	69.4	.220	$60	$1531	16.6
27	I	$489	68.3	74.7	.197	$39	$3058 − 812	12.4
	II	$475	71.1	75.7	.185	$40	$2246	11.3
36	I	$528	80.5	78.6	.166	$ 0	$3953 − 991	8.7
	II	$514	83.1	80.7	.153	$ 0	$2962	7.6
50	I	$613	92.1	83.7	.132	$ 0	$5345 −1259	5.0
	II	$600	93.8	86.9	.098	$ 0	$4076	3.9
75	I	$815	98.6	89.2	.096	$ 0	$7830 −1766	2.4
	II	$807	99.2	91.9	.053	$ 0	$6064	1.8
100	I	$1045	99.9	92.2	.076	$ 0	$10315 − 2200	1.5
	II	$1038	100.0	94.9	.036	$ 0	$ 8115	1.0

Table B-7. Summary of simulation results for house size I, insulation type III, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$465	33.6	63.5	.413	$66	$1347 − 404	23.0
	II	$442	35.3	66.9	.372	$74	$ 943	21.1
18	I	$423	65.5	76.4	.338	$104	$2319 − 664	12.8
	II	$401	68.7	79.8	.301	$112	$1655	11.0
27	I	$440	85.0	83.8	.304	$84	$3291 − 858	6.7
	II	$423	87.7	87.2	.251	$88	$2433	5.2
36	I	$488	95.5	89.6	.279	$32	$4263 −1053	3.1
	II	$475	96.8	93.1	.223	$31	$3210	2.1
50	I	$604	99.8	95.5	.251	$ 0	$5775 −1355	0.9
	II	$600	100.0	98.0	.199	$ 0	$4420	0.4
75	I	$847	100.0	99.5	.222	$0	$8475 −1895	0.1
	II	$846	100.0	99.9	.180	$0	$6580	0.2
100	I	$1127	100.0	99.99	.209	$0	$11175 − 2200	0.005
	II	$1127	100.0	99.99	.171	$0	$ 8975	0.001

Table B-8. Summary of simulation results for house size I, insulation type III, 2 cover collector.

AC sq ft)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
9	I	$466	34.6	64.3	.444	$64	$1424 − 427 $997	22.5
	II	$440	36.7	68.6	.400	$76		20.4
18	I	$427	67.9	78.1	.406	$100	$2474 − 695 $1779	11.8
	II	$404	71.2	81.9	.355	$109		10.0
27	I	$447	88.4	86.2	.384	$76	$3523 − 905 $2619	5.4
	II	$432	90.3	89.6	.334	$78		4.2
36	I	$503	97.6	92.8	.365	$14	$4573 −1115 $3458	1.9
	II	$494	98.7	95.4	.316	$17		1.2
50	I	$635	100.0	98.9	.344	$ 0	$6205 −1441 $4764	0.2
	II	$633	100.0	99.8	.300	$ 0		0.05
75	I	$907	100.0	99.99	.324	$ 0	$9120 −2024 $7096	0.002
	II	$907	100.0	99.99	.289	$ 0		0.002
100	I	$1228	100.0	99.99	.324	$ 0	$12035 − 2200 $ 9835	0.001
	II	$1228	100.0	99.99	.287	$ 0		0.001

Table 8-9. Summary of simulation results for house size I, insulation type III, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$1333	9.9	47.9	.351	$172	$1568 − 470 $1098	101.7
	II	$1288	11.0	49.3	.306	$186		98.0
24	I	$1256	22.6	56.0	.297	$248	$2761 − 752 $2009	86.5
	II	$1228	24.4	58.0	.271	$261		84.3
36	I	$1221	33.2	59.3	.259	$280	$3953 − 991 $2962	74.6
	II	$1219	34.7	63.7	.233	$280		74.3
48	I	$1223	41.4	62.7	.239	$277	$5146 −1229 $3917	65.5
	II	$1221	43.5	67.3	.231	$290		64.9
75	I	$1259	58.5	69.0	.194	$244	$7830 −1766 $6064	47.8
	II	$1253	59.5	72.3	.174	$254		47.3
100	I	$1353	69.9	74.1	.164	$147	$10315 − 2200 $ 8115	35.8
	II	$1345	70.4	76.5	.152	$163		35.2

Table B-10. Summary of simulation results for house size II, insulation type I, 1 cover collector.

AC sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$1287	13.2	52.5	.427	$218	$1671 − 501 $1170	37.20
	II	$1231	15.2	54.8	.392	$243		32.60
24	I	$1177	29.4	63.4	.375	$326	$2967 − 793 $2174	78.52
	II	$1139	31.4	64.1	.353	$348		75.4
36	I	$1123	42.4	69.3	.351	$377	$4263 −1053 $3210	64.1
	II	$1086	44.8	70.9	.325	$409		61.1
48	I	$1089	54.1	73.8	.335	$408	$5559 −1312 $4247	51.4
	II	$1064	55.7	75.9	.299	$436		49.4
75	I	$1105	73.7	80.8	.309	$386	$8475 −1895 $6580	30.3
	II	$1089	74.9	82.7	.262	$415		29.0
100	I	$1219	86.5	85.5	.289	$265	$11175 − 2200 $ 8975	16.6
	II	$1219	86.5	86.8	.224	$284		16.6

Table B-11. Summary of simulation results for house size II,
insulation type I, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$1288	13.8	52.8	.457	$217	$1774 − 532 $1242	96.6
	II	$1235	15.3	55.6	.413	$239		92.2
24	I	$1184	30.3	63.9	.430	$319	$3173 − 835 $2338	77.5
	II	$1137	32.4	66.8	.388	$349		73.7
36	I	$1128	44.1	70.2	.418	$371	$4573 −1115 $3458	62.2
	II	$1089	46.4	73.6	.370	$406		58.9
48	I	$1099	56.2	75.1	.409	$397	$5972 −1394 $4577	49.0
	II	$1067	58.2	77.9	.361	$431		46.4
75	I	$1120	77.1	82.6	.390	$368	$9120 −2024 $7096	26.6
	II	$1111	77.7	84.1	.343	$392		25.8
100	I	$1277	89.5	87.9	.375	$203	$12035 − 2200 $ 9835	13.1
	II	$1276	89.5	89.4	.330	$225		13.0

Table B-12. Summary of simulation results for house size II, insulation type I, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$794	17.5	52.3	.344	$139	$1568 − 470 $1098	54.0
	II	$772	19.0	54.8	.292	$154		52.6
24	I	$742	36.7	63.6	.255	$189	$2761 − 752 $2008	41.4
	II	$734	38.0	64.5	.242	$193		40.8
36	I	$746	51.1	68.4	.215	$184	$3953 − 991 $2962	32.5
	II	$738	53.0	70.1	.211	$191		31.9
48	I	$768	63.5	72.8	.191	$159	$5146 −1229 $3917	25.2
	II	$765	64.6	73.9	.183	$164		24.9
75	I	$886	81.7	79.8	.143	$35	$7830 −1766 $6064	14.3
	II	$884	82.0	80.2	.140	$42		14.1
100	I	$1052	91.8	84.1	.119	$0	$10315 − 2200 $8115	8.1
	II	$1051	91.6	84.8	.101	$0		8.0

Table B-13. Summary of simulation results for house size II, insulation type II, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$744	23.7	58.8	.417	$189	$1671 - 501 $1170	49.6
	II	$724	24.7	61.5	.380	$202		48.0
24	I	$671	47.3	71.0	.353	$259	$2967 - 793 $2174	34.0
	II	$655	49.2	73.1	.325	$272		32.7
36	I	$655	66.3	77.6	.326	$271	$4263 -1053 $3210	22.8
	II	$638	67.7	80.4	.279	$287		21.3
48	I	$676	80.0	82.4	.306	$246	$5559 -1312 $4247	14.5
	II	$665	80.7	84.7	.257	$258		13.6
75	I	$824	96.2	90.7	.270	$89	$8475 -1895 $6580	4.2
	II	$822	95.8	92.4	.223	$94		4.0
100	I	$1069	99.7	95.7	.246	$ 0	$11175 - 2200 $ 8975	1.2
	II	$1068	99.5	96.4	.204	$ 0		1.2

Table B-14. Summary of simulation results for house size II, insulation type II, 2 cover collector.

AC sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$750	23.8	59.2	.449	$182	$1774	49.4
	II	$727	25.1	62.8	.406	$199	$1242	47.5
24	I	$677	49.4	71.9	.417	$252	$3173	32.9
	II	$653	51.2	75.6	.369	$272	$2338	31.0
36	I	$661	69.2	79.4	.400	$264	$4573	20.8
	II	$645	70.3	82.2	.351	$279	$3458	19.5
48	I	$688	83.3	84.4	.386	$233	$5972	12.3
	II	$678	84.0	86.4	.339	$243	$4578	11.5
75	I	$862	98.3	94.0	.359	$47	$9120	2.3
	II	$861	98.1	94.8	.316	$51	$7096	2.3
100	I	$1158	100.0	99.2	.342	$ 0	$12035	0.2
	II	$1159	100.0	98.9	.303	$ 0	$ 9835	0.3

Note: In the SOLAR SYSTEM COST column the values show subtractions:
- 12: $1774 − 532 = $1242
- 24: $3173 − 835 = $2338
- 36: $4573 − 1115 = $3458
- 48: $5972 − 1394 = $4578
- 75: $9120 − 2024 = $7096
- 100: $12035 − 2200 = $ 9835

Table B-15. Summary of simulation results for house size II, insulation type II, 3 cover collector.

AC sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$679	24.6	56.0	.335	$37	$1568 − 470 $1098	36.5
	II	$653	25.9	58.7	.282	$46		34.4
24	I	$652	47.9	68.4	.242	$63	$2761 − 752 $2009	25.4
	II	$629	51.0	68.9	.221	$70		23.6
36	I	$669	66.1	74.2	.195	$43	$3953 − 991 $2962	17.7
	II	$651	68.9	75.0	.188	$47		16.2
48	I	$716	78.8	78.2	.164	$ 0	$5146 −1229 $3917	12.5
	II	$701	80.7	79.8	.156	$ 0		11.2
75	I	$887	93.7	84.9	.122	$ 0	$7830 −1766 $6064	5.8
	II	$873	94.9	87.7	.085	$ 0		4.6
100	I	$1099	98.0	88.8	.098	$ 0	$10315 − 2200 $ 8115	3.4
	II	$1089	98.6	91.2	.056	$ 0		2.6

Table B-16. Summary of simulation results for house size II, insulation type III, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$631	32.7	63.5	.407	$84	$1671 - 501 $1170	31.8
	II	$605	33.9	66.7	.369	$93		30.0
24	I	$582	63.5	75.9	.338	$130	$2967 - 793 $2174	18.4
	II	$557	65.9	79.1	.302	$139		16.2
36	I	$600	83.2	83.2	.306	$107	$4263 -1053 $3210	9.7
	II	$580	86.3	85.3	.253	$112		8.1
48	I	$660	94.1	88.8	.282	$42	$5559 -1312 $4247	4.7
	II	$646	95.2	91.9	.227	$42		3.5
75	I	$887	100.0	96.6	.244	$ 0	$8475 -1895 $6580	0.8
	II	$881	100.0	98.5	.195	$ 0		0.4
100	I	$1160	100.0	99.3	.224	$ 0	$11175 - 2200 $ 8975	0.2
	II	$1159	100.0	99.8	.182	$ 0		0.1

Table B-17. Summary of simulation results for house size II, insulation type III, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
12	I	$632	33.8	64.3	.441	$33	$1774 -532 $1242	31.3
	II	$605	34.9	68.3	.400	$94		29.0
24	I	$586	66.0	77.5	.406	$125	$3173 -835 $2338	17.0
	II	$559	68.7	81.3	.356	$136		14.7
36	I	$610	86.3	85.4	.385	$96	$4573 -1115 $3458	8.2
	II	$591	88.3	88.5	.336	$100		6.6
48	I	$679	96.7	92.0	.367	$21	$5972 -1394 $4578	3.0
	II	$667	97.8	94.5	.318	$19		2.1
75	I	$939	100.0	99.6	.340	$ 0	$9120 -2024 $7096	0.9
	II	$938	100.0	99.9	.297	$ 0		0.3
100	I	$1259	100.0	99.99	.323	$ 0	$12035 -2200 $ 9835	0.02
	II	$1259	100.0	99.99	.290	$ 0		0.02

Table B-13. Summary of simulation results for house size II,
insulation type III, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$1721	9.9	48.0	.346	$225	$1866 − 560 $1306	132.4
	II	$1678	10.8	49.2	.300	$241		128.6
30	I	$1634	21.8	55.5	.273	$311	$3357 − 871 $2486	114.1
	II	$1610	23.5	57.7	.270	$328		111.9
45	I	$1594	31.8	58.7	.253	$348	$4848 −1170 $3678	99.2
	II	$1590	33.4	63.2	.233	$361		98.9
60	I	$1590	40.5	61.8	.233	$358	$6339 −1468 $4871	87.4
	II	$1582	41.9	66.9	.208	$370		86.7
75	I	$1605	47.8	64.7	.216	$342	$7830 −1766 $6064	77.2
	II	$1596	49.2	69.6	.191	$361		76.4
100	I	$1669	59.1	68.9	.192	$291	$10315 − 2200 $8115	62.7
	II	$1645	59.5	73.1	.170	$304		60.7

Table B-19. Summary of simulation results for house size III, insulation type I, 1 cover collector.

A.E (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$1664	13.1	52.5	.424	$282	$1995 − 599 / $1396	126.8
	II	$1614	14.2	54.3	.390	$303		122.7
30	I	$1529	28.6	63.1	.375	$414	$3615 − 923 / $2692	103.4
	II	$1504	29.8	63.5	.354	$432		101.3
45	I	$1461	41.1	68.8	.352	$479	$5235 −1247 / $3998	85.3
	II	$1432	42.9	70.2	.326	$516		82.3
60	I	$1416	52.5	73.3	.337	$521	$6855 −1571 / $5234	69.2
	II	$1400	53.6	75.2	.302	$554		67.9
75	I	$1404	62.0	76.7	.325	$529	$8475 −1895 / $6580	55.8
	II	$1395	62.8	78.5	.281	$564		55.0
100	I	$1468	74.8	81.2	.307	$461	$11175 − 2200 / $8975	39.2
	II	$1464	75.2	82.8	.262	$498		37.3

Table B-20. Summary of simulation results for house size III,
insulation type I, 2 cover collector.

-97-

NO. AT (?)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$1673	13.2	52.6	.466	$273	$2124 - 625 $1499	126.5
	II	$1615	14.7	55.5	.413	$302		121.8
30	I	$1549	28.8	63.4	.430	$394	$3873 - 975 $2898	102.9
	II	$1498	31.0	66.2	.389	$437		98.8
45	I	$1474	42.4	69.5	.419	$466	$5622 -1324 $4298	83.4
	II	$1440	44.1	72.7	.371	$506		80.6
60	I	$1431	54.3	74.5	.409	$505	$7371 -1674 $5697	66.4
	II	$1409	55.6	76.9	.363	$543		64.7
75	I	$1423	64.3	78.1	.401	$509	$9120 -2024 $7096	52.8
	II	$1407	65.4	80.4	.354	$550		51.0
100	I	$1518	78.0	82.9	.389	$414	$12035 - 2200 $ 9835	33.4
	II	$1512	78.0	84.3	.342	$446		33.8

Table 3-21. Summary of simulation results for house size III,
insulation type I, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$1031	16.1	52.1	.340	$169	$1866 - 560 $1306	71.8
	II	$1004	18.3	54.6	.290	$196		69.6
30	I	$965	35.4	62.8	.253	$238	$3357 - 871 $2486	55.1
	II	$964	36.1	64.0	.244	$235		55.0
45	I	$967	49.3	67.6	.219	$231	$4848 -1170 $3678	43.8
	II	$965	50.4	69.6	.210	$238		43.6
60	I	$996	61.7	71.6	.195	$207	$6339 -1468 $4871	34.8
	II	$988	61.8	73.4	.183	$209		34.0
75	I	$1045	70.7	75.5	.169	$150	$7830 -1766 $6064	27.2
	II	$1042	71.1	76.3	.163	$160		26.9
100	I	$1174	82.3	80.1	.139	$17	$10315 - 2200 $ 8115	18.0
	II	$1170	82.4	80.1	.138	$28		17.8

Table B-22. Summary of simulation results for house size III, insulation type II, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$963	22.7	58.4	.414	$237	$1995 - 599 $1396	65.4
	II	$947	23.5	61.1	.378	$253		64.1
30	I	$878	45.6	70.3	.354	$318	$3615 - 923 $2692	46.0
	II	$859	47.2	72.5	.326	$342		44.4
45	I	$850	64.2	76.8	.328	$343	$5235 -1247 $3988	31.3
	II	$835	65.1	79.5	.284	$365		30.0
60	I	$870	77.8	81.8	.308	$318	$6855 -1571 $5284	20.4
	II	$865	77.8	83.8	.261	$333		20.0
75	I	$929	87.2	85.6	.291	$256	$8475 -1895 $6580	12.7
	II	$925	87.4	87.3	.244	$270		12.5
100	I	$1118	95.7	91.0	.268	$60	$11175 - 2200 $ 8975	5.2
	II	$1116	96.4	92.2	.223	$71		5.1

Table B-23. Summary of simulation results for house size III, insulation type II, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$973	22.8	58.9	.448	$227	$2124 − 625 $1499	65.2
	II	$949	24.0	62.5	.405	$251		63.3
30	I	$887	47.1	71.1	.418	$310	$3873 − 975 $2898	44.7
	II	$860	48.9	74.9	.370	$340		42.5
45	I	$859	66.7	78.5	.402	$333	$5622 −1324 $4298	28.9
	II	$845	67.5	81.4	.353	$354		27.8
60	I	$885	81.0	83.7	.388	$302	$7371 −1674 $5697	17.7
	II	$880	81.0	85.5	.341	$317		17.5
75	I	$955	90.1	88.1	.376	$226	$9120 −2024 $7096	9.9
	II	$952	90.4	89.9	.329	$241		9.7
100	I	$1190	98.0	94.3	.358	$ 0	$12035 − 2200 $ 9835	2.8
	II	$1187	98.6	94.8	.315	$ 0		2.6

Table B-24. Summary of simulation results for house size III, insulation type II, 3 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$869	24.0	56.0	.331	$44	$1866	47.3
	II	$841	25.1	58.7	.279	$55	$\frac{-\ 560}{\$1306}$	45.1
30	I	$837	46.8	68.1	.239	$74	$3357	33.4
	II	$815	49.1	68.4	.223	$80	$\frac{-\ 871}{\$2486}$	31.6
45	I	$858	64.5	73.8	.194	$50	$4848	23.6
	II	$842	66.4	74.1	.191	$52	$\frac{-1170}{\$3678}$	22.3
60	I	$918	76.5	77.6	.165	$ 0	$6339	17.3
	II	$902	78.2	78.7	.159	$ 0	$\frac{-1468}{\$4871}$	15.7
75	I	$996	85.7	80.9	.144	$ 0	$7840	12.0
	II	$981	86.7	82.9	.127	$ 0	$\frac{-1766}{\$6064}$	10.8
100	I	$1175	94.1	86.3	.117	$ 0	$10315	6.9
	II	$1162	94.8	87.7	.081	$ 0	$\frac{-\ 2200}{\$\ 8115}$	5.8

Table B-25. Summary of simulation results for house size III, insulation type III, 1 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$811	31.7	63.1	.403	$101	$1995 − 599 $1396	41.8
	II	$800	33.1	66.5	.367	$115		39.2
30	I	$753	61.5	75.4	.339	$155	$3615 − 923 $2692	24.5
	II	$724	63.7	78.6	.303	$169		22.2
45	I	$770	81.3	82.5	.308	$133	$5235 −1247 $3988	13.5
	II	$748	82.8	85.6	.256	$141		11.7
60	I	$840	92.8	87.9	.284	$58	$6855 −1571 $5284	6.7
	II	$824	93.5	91.0	.231	$60		5.4
75	I	$949	97.9	92.3	.265	$ 0	$8475 −1895 $6580	3.2
	II	$937	98.4	94.7	.213	$ 0		2.2
100	I	$1202	100.0	96.9	.242	$ 0	$11175 − 2200 $ 8975	0.9
	II	$1197	100.0	98.3	.195	$ 0		0.5

Table B-26. Summary of simulation results for house size III, insulation type III, 2 cover collector.

AC (sq m)	HEAT LOSS MODEL	ANNUAL ENERGY COST	% SOLAR SPACE HEAT	% SOLAR HOT WATER	SOLAR SYSTEM ANNUAL EFF.	ANNUAL SAVINGS	SOLAR SYSTEM COST	AUXILIARY ENERGY (million kilojoules)
15	I	$815	32.7	63.8	.440	$97	$2124 - 625 $1499	41.1
	II	$783	33.6	68.2	.400	$112		38.4
30	I	$756	64.2	77.0	.407	$151	$3873 - 975 $2898	22.8
	II	$728	66.2	80.5	.358	$164		20.5
45	I	$782	84.4	84.6	.387	$120	$5622 -1324 $4298	11.4
	II	$763	85.7	87.4	.338	$125		9.9
60	I	$862	95.5	91.0	.369	$33	$7371 -1674 $5697	4.6
	II	$850	96.2	93.5	.320	$32		3.5
75	I	$988	99.5	95.8	.354	$ 0	$9120 -2024 $7096	1.5
	II	$982	99.5	97.3	.310	$ 0		1.0
100	I	$1293	100.0	99.7	.338	$ 0	$12035 - 2200 $ 9835	0.09
	II	$1293	100.0	99.8	.297	$ 0		0.05

Table B-27. Summary of simulation results for house size III, insulation type III, 3 cover collector.

APPENDIX C

COMPUTER PROGRAM LISTING

95

```
//brooks Job --------,'brooks,doug',class=a,time=(4,00)
/*Jobparm d=rmt1
//*   usr=(dmbrook,/bin/sus,1)
// exec forascls,parm.fort=nosource
//fort.sysin dd *
      real ms,mce,mcps,lfsv1,lfsv2
      INTEGER*2 KDATA(8)
      dimension sum(18),csti(3,3)
      data csti(1,1),csti(1,2),csti(1,3)/-26.82,0.0,73.07/
      data csti(2,1),csti(2,2),csti(2,3)/-38.02,0.0,104.01/
      data csti(3,1),csti(3,2),csti(3,3)/-49.97,0.0,137.09/
      print 44
      print 44
      print 161
c
c   enter data values for latitude,collector tilt, collector
c   azimuth - all in degrees.
c
      ph=35.50
      beta=50.5
      gama=0.0
c
c   enter values for max collector size,acmx, no. of glass covers,n,
c   design room temperature, and upper limit for service hot
c   water temperature.
c
      acmx=125.
      n=2
      tr=293.16
      tr2=291.48
      thw=333.16
c
c   enter values for collector cost/sq m, storage cost/sq m,
c   piping and equipment costs, equivalent uniform annual
c   cost factor,present worth factor, and fuel costs/million kj.
c
      nm2=n-2
      ccost=100.+8.6*float(nm2)
      stcst=8.0
      ce=375.
      euacf=.11746
      euac3=.10185
      pwf=8.932
      cf=.000006
c
c   enter flag for type radiaton values on this data tape
c
c      itype=0   no direct normal values on tape.
c      itype.ne.0   direct normal values are available.
c
      itype=0
c
c   enter size(isize),design air temp
c   (tdesn), design wind speed(,vdesn), max and min ground temperatures
c   (tgmax,tgmin).
c
```

```
      insul=2
      isize=2
      tdesn=279.2
      vdesn=11.5
      tsmax=294.4
      tsmin=286.46
      tsmn=(tsmax+tsmin)/2.
      tsamp=(tsmax-tsmin)/2.
      print 159
      write(6,162) tdesn,vdesn,tsmin,tsmax
      print 44
c
      do 900 nac=1,4
      ac=0.2*acmx*float(nac)
      cfuel=cf*ac*euac3*20.
c  call subroutine initial to calculate initial one time constants
c  for the station, house, and collector used.
      call initl(ph,beta,gama,sinph,cosph,tanph,sinb,cosb,
     1sins,coss,ac,ms,mcps,us,tsold,str1s,tpp,flo,rho,vdesn,
     1ul,mce,cpc,fr,n,exptrm,absor,flow,fp,ex,fc,fcc,str12,tso12)
c
      print 44
      print 44
      print 158
      write(6,40) ms,flo,ex,n,ul,fr
c
c  call subroutine design to compute station specific house
c  parameters, areas of house surfaces, area-u value  products
c  for exposed surfaces, design heat loss/deg c, and infiltration
c  loss.
      call design(ac,beta,isize,insul,tdesn,achs,a,b,c,d,e,
     1arn,ars,ahs,araw,awins,aws,awinn,awn,awine,awen,aud,vdesn,
     1arun,arus,aruaw,auc,auwin,auw,aufl,auc2,ausum,urf,adesn,
     1adinf,samin,uc,uw,us,uaw,ud,ufl,adr,fc,aub,tsmin,vahw,
     1achw,achs,vol)
c
c  print all house parameters.
      print 44
      print 5,isize,insul
      samin=samin*57.28
      h11=2.*aud/adesn*100.
      h12=auwin/adesn*100.
      h13=aufl/adesn*100.
      h14=auw/adesn*100.
      h15=auc/adesn*100.
      h16=adinf/adesn*100.
      htl=h11+h12+h14+h13+h15+h16
      print 7
      print 6,h11,h12,h13,h15,h14,h16,htl
      print 88
      print 6,a,b,c,d,e,samin
      samin=samin/57.28
      print 9
      print 21,arn,ars,ahs,araw,awins,aws,awinn,awn,awine,awen
      print 10
      print 21,aud,arun,arus,aruaw,auwin,auw,aufl,auc,ausum
```

```
      print 11
      print 21,qdesn,qdinf,achs,ac
      print 44
      hl=qdesn
      IDAY=0
c
c   run the model for the design year
c
      do 64 J=1,18
   64 sum(J)=0.
      DO 1 J=1,365
      IDAY=IDAY+1
      DAY=FLOAT(IDAY)
c compute declination, cos and sin of declination..
      arg=(360.*(284.+day)/365.)*.01745329
      delt=(23.45*sin(arg))*.01745329
      sdelt=sin(delt)
      cdelt=cos(delt)
      arg2=arg-.516426
c   compute ground temperature for this day
      tg=tgmn+tgamp*sin(arg2)
c   compute basement losses/hr for this day.
      bls=aub*(tr-tg)
      if(bls.le.0) bls=0.
      if(iday.gt.150.and.iday.lt.255) bls=0.
      DO 1 I=1,24
c read weather and solar radiation parameters for each hour.
      READ(4,4) (KDATA(nv),nv=1,8)
    4 FORMAT(8A2)
      IRHT=KDATA(4)
      MODA=KDATA(1)
      ITIME=KDATA(2)
      TIME=FLOAT(ITIME)
      ITEMP=KDATA(5)
      ta=float(itemp)/10.
      ta=ta+273.16
      IDN=KDATA(3)
      rdn=float(idn)
      DN=FLOAT(IDN)
      RHT=FLOAT(IRHT)
      IC=KDATA(8)
      CC=FLOAT(IC)
      IWIND=KDATA(6)
      WIND=FLOAT(IWIND)
      ISPED=KDATA(7)
      SPEED=(FLOAT(ISPED))/10.
c set initial solair temperatures to dry bulb temperature.
      tern=ta
      ters=ta
      teww=ta
      teew=ta
      tesw=ta
      tenw=ta
      alpha=0.
      theta=1.570716
c
```

```
c   if radiation values are greater than 0, compute the incidence
c   angle on the collector and all building surfaces. If the
c   angle of incidence on any surface exceeds 90 deg, set it = 90.
c

      if(idn.le.0.or.idn.gt.9998) rdn=0.
      if(irht.le.0.or.irht.gt.9998) rht=0.
      if(irht.le.0.or.irht.gt.9998)  go to 8
c
      call angle(sinph,cosph,tanph,sinb,cosb,sing,cosg,
     1day,time,theta,alpha,angws,angwe,angww,angnr,
     1samin,angnw,ph,sina,costh,cdelt,sdelt)
c
    8 continue
c
c   call subroutine collector to compute the solar radiation incident
c   on each collector and the useful energy collected, if any, by each.
c
      call coll(ac,fr,ul,tsold,ta,tpp,flo,cpc,tco,rdn,rht,cc,
     1itype,alpha,theta,beta,rho,qu,ac,rd,rdu,irht,speed,n,uls,qu2,
     1cosb,sina,costh,mce,exptrm,absor,wind,fcc,tsol2,ult,fp)
c
      sum(1)=sum(1)+qc
c
c   if the sun is up, calculate the solair temperature of each
c   exposed building surface.
c
      solgn=0.
      if(alpha.le.0.2) go to 102
      call solair(angws,angwe,angww,angnr,theta,tern,ters,teew,
     1teww,tesw,tenw,rdn,rdu,angnw,speed)
c
      call shg(angwe,rdn,rdu,insul,shgn,moda)
      solgn=solgn+shgn*awine
      call shg(angws,rdn,rdu,insul,shgn,moda)
      solgn=solgn+awins*shgn
      call shg(angww,rdn,rdu,insul,shgn,moda)
      solgn=solgn+shgn*awine
      call shg(angnw,rdn,rdu,insul,shgn,moda)
      solgn=solgn+shgn*awinn
  102 continue
c
c   set energy requirements for service hot water for this hour.
c
      qshw=0.
      qshw2=0.
      if(itime.gt.5.and.itime.lt.21) qshw=vqhw*(thw-ts)
      qshw2=qshw
      sum(4)=sum(4)+qshw/ac
c
c   compute building heat demand using design heat transmission
c   coefficient (computed in subroutine design).
c
      hls=0.
      if(ta.lt.tr2) hls=hl*(tr2-ta)
      qload=hls-strls
      if(qload.lt.0.) qload=0.
```

```
      sum(9)=sum(9)+qload/ac
      sum(5)=sum(5)+hls/ac
      sum(6)=sum(6)+strls/ac
c
c   compute storage temperature and storage losses for this hour.
      call strge(ac,flo,qu,qload,tsold,tsnew,qdump,qaux,strls,
     1qshw,qaxw,vqhw,ms,mcps,us)
      sum(12)=sum(12)+qaux/ac
      sum(13)=sum(13)+qaxw/ac
c
c   compute building heat demand as a function of temperature,
c   wind, and radiation influences.
c
      heatl=0.
      call demand(speed,wind,fc,awen,awine,araw,uw,us,teew,aws,awins,
     1adr,ud,tesw,ars,urf,ters,teww,awn,awinn,arn,tenw,tern,auc2,ac,
     1tpp,achw,achs,vol,bls,aub,heatl,winls,hli,ta)
c
      sum(7)=sum(7)+heatl/ac
      sum(8)=sum(8)+strl2/ac
      ql=heatl-strl2
      if(ql.lt.0.) ql=0.
      if(solgn.ge.ql) solgn=ql
      sum(10)=sum(10)+solgn/ac
      sum(11)=sum(11)+hli/ac
       l=ql-solgn
      if(ql.lt.0.) ql=0.
      sum(18)=sum(18)+ql/ac
c
c   compute storage temperature and storage losses for the expanded
c   parameter model.
      call strge(ac,flo,qu,ql,tsol2,tsnw2,qdmp2,qaux2,strl2,
     1qshw2,qaxw2,vqhw,ms,mcps,us)
      sum(14)=sum(14)+qaux2/ac
      sum(15)=sum(15)+qaxw2/ac
      sum(16)=sum(16)+winls/ac
      sum(17)=sum(17)+bls/ac
      sum(2)=sum(2)+qu/ac
      sum(3)=sum(3)+qu2/ac
c
    1 continue
c
c   compute annual efficiency,equivalent uniform annual costs,
c   percentage solar, annual savings for each system.
c
      anef1=sum(2)/sum(1)
      anef2=sum(3)/sum(1)
      colcs=(ccost+stcst)*ac+ce
      if(colcs.gt.2000.) taxsv=600.+0.2*(colcs-2000.)
      if(colcs.le.2000.) taxsv=0.3*colcs
      if(colcs.ge.10000.) taxsv=2200.
      ccfn=colcs-taxsv
      euac1=ccfn*euacf+(sum(12)+sum(13))*cfuel+csti(isize,insul)
      euac2=ccfn*euacf+(sum(14)+sum(15))*cfuel+csti(isize,insul)
c
      phw1=(1.-sum(13)/sum(4))*100.
```

```
      phw2=(1.-sum(15)/sum(4))*100.
      psht1=(1.-sum(12)/sum(9))*100.
      psht2=(1.-sum(14)/sum(18))*100.
c
      fcst1=cfuel*(sum(9)+sum(4))
      fcst2=cfuel*(sum(18)+sum(4))
      if(fcst1.le.euac1) ansv1=0.
      if(fcst2.le.euac2) ansv2=0.
      if(fcst1.st.euac1) ansv1=fcst1-euac1
      if(fcst2.st.euac2) ansv2=fcst2-euac2
      lfsv1=ansv1*pwf
      lfsv2=ansv2*pwf
c
c   print results
      do 333 jk=1,18
  333 sum(jk)=sum(jk)*ac
      print 300
      print 100
      write(6,99) (sum(kk),kk=1,9)
      print 200
      write(6,99) (sum(kk),kk=10,18)
      print 44
      cful=cfuel/ac
      print 400,ccost,cful
      print 151,euac1,anef1
      print 153,phw1,psht1
      print 152,euac2,anef2
      print 153,phw2,psht2
      print 163,csti(isize,insul)
      print 44
      print 155,colcs,taxsv,ccfn
      print 156,ansv1,lfsv1
      print 157,ansv2,lfsv2
      print 44
c
      REWIND 4
  900 continue
c
   21 format(10(1x,f12.2))
   44 format(1x,//,1x,120('*'),/)
    5 format(1x,'house size ',i2,5x,'insulation level ',i2,/)
    6 format(10(1x,f11.2))
    9 format(1x,/,6x,'house surface areas',/,
     16x,'north roof   south roof-ac house area   attic walls',
     1' s windows  south walls   n windows   north walls',
     1' end windows  end walls ')
   88 format(1x,/,5x,'a,roof ht  b,n-roof ln   c,dis to pk',
     1' d,s-roof ln e,hwd-c    slope n-roof')
    7 format(1x,/,6x,'%hl doors  %hl windows %hl basemt  %hl ceil'
     1,'ns   %hl walls  %hl infilt  total %')
   10 format(1x,/,6x,'area u-value products',/,
     16x,' doors       north roof  south roof-ac attic walls',2x,
     1' windows       walls        floors      ceiling   sum')
   11 format(1x,/,1x,'design loss/des c  design infil/c  achs/hr',
     1' area collector')
   99 format(1x,9(e11.4,1x),/)
```

```
100 format(1x,/,1x,'incid. rad.',1x,'qu coll 1',3x,'qu coll2',3x,
   1'hot water',3x,'Heat loss 1',1x,'strge lss 1',1x,'heat loss 2',1x,
   1'strge lss 2',1x,'heat load 1',/)
200 format(1x,/,1x,'solar gain ',1x,'infiltration',1x,'auxilliary 1',
   11x,'aux hw 1',1x,'auxilliary 2',1x,'aux hw 2',4x,'wndow loss',2x,
   1'bsmt loss',3x,'heat load 2',/)
151 format(1x,/,1x,'the standard system has equivalent annual costs',
   1' of',f10.2,' dollars, with annual efficiency of ',f8.4,//)
152 format(1x,/,1x,'the expanded parameter system has equivalent',
   1' annual costs of ',f10.2,' dollars, with annual efficiency of',
   1f8.4,//)
300 format(1x,'annual energy totals:',/)
400 format(1x,'annual cost and efficiency analyses for collector ',/,
   11x,'costs of ',f8.2,' dollars per sq m and fuel costs of ',f10.8,
   1'dollars per kiloJoule:',/,/)
153 format(1x,'it provides ',f8.3,' % of hot water and ',
   1f8.3,' % of space heat',/)
155 format(1x,'the system cost above base is ',f10.2,
   1' dollars ',/,1x,'a tax break of ',f10.2,' dollars',
   1' reduces this to a final cost of ',f10.2,' dollars',/)
156 format(1x,' the annual energy savings for system 1 are',
   1f10.2,' dollars, and the present worth of the lifetime',/,1x,
   1' savings, with money valued at 8% is ',f10.2,'dollars',/)
157 format(1x,' the annual energy savings for system 2 are',
   1f10.2,' dollars, and the present worth of the lifetime',/,1x,
   1' savings, with money valued at 8% is ',f10.2,'dollars',/)
158 format(1x,'collector and storage parameters:',/,
   11x,'mass of storage',1x,'mass flow rate/sq m of col.',1x,
   1'heat exchanger coef.',1x,'no. of glass covers',1x,
   1'col. u loss',1x,'heat removal factor',/)
 40 format(1x,f15.1,6x,f15.2,8x,f15.4,4x,i8,8x,f11.2,3x,f15.4,/)
159 format(1x,'design weather parameters:',/,
   11x,'design air temp',1x,'design wind sp',1x,
   1'winter ground temp',1x,'summer ground temp',/)
161 format(1x,'oklahoma city',//)
162 format(1x,f15.2,1x,f14.2,3x,f15.2,3x,f15.2,/)
163 format(1x,'the equivalent uniform annual cost of insulation is',
   1f8.2,' dollars',//)
    STOP
    end
//go.ft04f001 dd dsn=d.brooks.staa,disp=shr
//
/*eof
```

```
      subroutine design(ac,beta,isize,insul,tdesn,achs,a,b,c,d,e,
     1arn,ars,ahs,araw,awins,aws,awinn,awn,awine,awen,aud,vdesn,
     1arun,arus,aruaw,auc,auwin,auw,aufl,auc2,ausum,urf,qdesn,
     1qdinf,samin,uc,uw,us,uaw,ud,ufl,adr,fc,aub,tsmin,vqhw,
     1achw,achs,vol)
c
c********************************************************************
c
c
c
c                          /            /
c                       /         (
c                    /          tilt
c                 /              /!
c              /              /   !
c           /             /      !
c        /             /         !
c     /            /        /
c   /           /        /
c /          /        /hlen
c         !        !     /
c    ht!          !    /
c         !        !  /
c         !_____!/
c              hwd
c********************************************************************
c
c this subroutine calculates the design heat loss for the
c    structure under consideration as a function of the
c       llector size, the tilt of the collector, the size
c    and degree of insulation of the various components of
c    the structure, and the design temperature and number of
c    airchanges per hour for the structure.  The three house
c    sizes (isize =1,2, or 3) are 92.9 sq m, 134.8 sq m, and
c    180 sq m.  The three levels of insulation (insul =1,
c    2, or 3) are poor, moderate, and heavy - relative terms.
c    the subroutine has a table of values for u for all the
c    components for each level of insulation, as well as the
c    dimensions of each of the basic house sizes.  The roof
c    dimensions vary with location, since the collector is
c    taken as an integral part of the roof. These dimensions
c    are calculated in this subroutine.
c
c the outputs are the areas of the surfaces of the structure,
c the dimensions of the roof structure (calculated here so
c that the collector is an integral part of the roof at a
c tilt beta), the design area-uvalue products for all of the
c house components, and the design infiltration and overall
c heat transmission coefficient for the house.
c
c********************************************************************
c   dimension design air-change values and u-values.
c
      dimension acw(3),acs(3)
      dimension uct(3),uwt(3),uflt(3),ust(3),uawt(3),urft(3),udt(3)
c
c   dimension array for house component sizes.
```

```
c
      dimension ah(3),hlen(3),hwd(3),ht(3),fl(3),awin(3),ad(3)
c
c   enter design u-values and air-change values in table;
c
      data uct(1),uct(2),uct(3)/3.883,1.627,0.850/
      data uwt(1),uwt(2),uwt(3)/5.070,2.780,1.463/
      data uflt(1),uflt(2),uflt(3)/7.162,2.773,2.168/
      data ust(1),ust(2),ust(3)/25.409,10.681,9.751/
      data uawt(1),uawt(2),uawt(3)/8.856,8.856,5.928/
      data urft(1),urft(2),urft(3)/12.388,12.388,9.975/
      data udt(1),udt(2),udt(3)/7.563,6.541,5.724/
      data acw(1),acw(2),acw(3)/.030,.0225,.015/
      data acs(1),acs(2),acs(3)/.0216,.0162,.0108/
c
c   enter dimension of each house type in table;
c
      data ah(1),hlen(1),hwd(1),ht(1),fl(1),awin(1),ad(1)/
     192.9,12.2,7.62,2.44,39.6,9.67,5.0/
      data ah(2),hlen(2),hwd(2),ht(2),fl(2),awin(2),ad(2)/
     1134.8,14.25,9.5,2.74,47.5,13.5,6.7/
      data ah(3),hlen(3),hwd(3),ht(3),fl(3),awin(3),ad(3)/
     1180.,15.0,12.0,3.05,54.0,17.67,7.31/
c
      cpa=1.20719
      radcon=.01732945
      ars=beta*radcon
      ars2=(90.-beta)*radcon
      snb=sin(ars)
      snb2=sin(ars2)
c
c
      i=isize
      in=insul
      d=ac/(hlen(i)*0.8)
      a=snb*d
      c=snb2*d
      e=hwd(i)-c
      tars=a/e
      samin=atan(tars)
      b=(a*a+e*e)**0.5
c   compute area of north and south facing roof surfaces.
      arn=b*hlen(i)
      ars=d*hlen(i)-ac
c   compute area of attic walls.
      ahs=ah(i)
      araw=0.5*a*hwd(i)
c   compute area of south facing windows.
      awins=awin(i)*0.6
c   compute area of south facing wall surface.
      aws=hlen(i)*ht(i)-ad(i)/2.-awins
c   compute area of north facing windows and walls.
      awinn=awin(i)*.2
      awn=hlen(i)*ht(i)-ad(i)/2.-awinn
c   compute area of window glass and walls on ends of house.
      awine=awin(i)*.1
```

```
      awen=hwd(i)*ht(i)-awine
      adr=ad(i)/2.
c compute effective volume-density of inside of house for infiltration.
      vol=ahs*ht(i)*cpa
c set design infiltration load due to wind and stack effects.
      achw=acw(in)
      achs=acs(in)
      achg=.10+achs*(291.5-tdesn)+achw*vdesn
      qdinf=vol*achg
c set design u-values for each surface for this house.
      uc=uct(in)
      uw=uwt(in)
      us=ust(in)
      uaw=uawt(in)
      urf=urft(in)
      ud=udt(in)
      ufl=uflt(in)
c compute design area-u value products for this house.
      aud=adr*ud
      arun=arn*urf
      arus=ars*urf
      aruaw=araw*uaw
      auc=ahs*uc
      auwin=awin(i)*us
      auwn=awn*uw
      auws=aws*uw
      auwen=awen*uw
      auw=auwn+auws+2.*auwen
      aub=ufl*fl(i)
      aufl=aub*(291.5-tgmin)/(291.5-tdesn)
      auc2=auc*295.16
      ausum=auc+arun+arus+2.*aruaw+ac*urf
c   calculate design attic temperature
      desnat=tatic(auc2,tdesn,arun,tdesn,arus,ac,urf,tdesn,
     1tdesn,tdesn,aruaw,aruaw,ausum)
c   calculate design heat transmission coefficient.
      qdesn=auw+auwin+aufl+auc+2.*aud+qdinf
      uw=1./uw-fc
      uaw=1./uaw-fc
      ud=1./ud-fc
      us=1./us-fc
      urf=1./urf-fc
c   set hourly energy requirements for hot water based on
c   house size.
c   75kg/person-day
c   4 persons for size 1
c   5 persons for size 2
c   6 persons for size 3
      kv=isize-1
      vqhw=((300.+float(kv)*75.)*4.19)/15.
      return
      end
```

```
      function tatic(auc2,tern,arun,ters,arus,ac,urf,tpp,teew,teww,
     1aruae,aruaw,ausum)
c  this subroutine calculates the temperature of attic
c  using the proceedure given in ashrae,ch 25,p440.
      tatic=(auc2+tern*arun+ters*arus+ac*urf*ters+teew*aruae
     1+teww*aruaw)/ausum
       return
       end
```

```
c************************************************************
c
      subroutine initl(ph,beta,sama,sinph,cosph,tanph,sinb,cosb,
     1sins,coss,ac,ms,mcps,us,tsold,strls,tpp,flo,rho,vdesn,
     1ul,mce,cpc,fr,n,exptrm,absor,flow,fp,ex,fc,fcc,strl2,tsol2)
c
c   This subroutine takes station latitude,ph,collector tilt,      c
c   beta, and the collector azimuth angle, sama and computes       c
c   the trigonometric one time calculations needed for sub-        c
c   routine,angle,and initializes values for subroutine storage,
c   collector, and design.
c   input values for all angles are in degrees.
c
c************************************************************
c
      real ms,mcps,mce
      dimension f(3),ult(3),tmce(3),frt(3)
      data f(1),f(2),f(3)/.95,.98,.99/
      data frt(1),frt(2),frt(3)/.786,.824,.901/
      data ult(1),ult(2),ult(3)/28.8,14.4,7.2/
      data tmce(1),tmce(2),tmce(3)/6.6,10.66,15.22/
      vcdesn=5.
      radcv=.01745329
      epsl=.1111
      p=ph*radcv
      b=beta*radcv
      s=sama*radcv
      sinph=sin(p)
      cosph=cos(p)
      tanph=tan(p)
      sinb=sin(b)
      coss=cos(s)
      cosb=cos(b)
      sins=sin(s)
c   set storage mass
      ms=61.*ac
c    set heat capacity of storage mass, deg c/kj.
      mcps=1./(ms*4.19)
c    compute area of cylindrical storage vessel for this storage mass.
      area=9.4247779*((ms/9424.7)**.66667)
c    compute heat transmission coefficient for storage vessel.
      us=1.44*area
c    initialize storage temp,storage loss,plate temp,rho.
      tsold=333.16
      tsol2=333.16
      strls=0.
      strl2=0.
      tpp=273.16
      rho=0.2
c    specific heat of water -   kj/(kg - deg c).
      cpc=4.19
c    set collector heat loss coefficient for n covers, kj/deg c.
      ul=ult(n)
c    set effective collector heat capacity -  deg c/(kj - sq m).
      mce=tmce(n)
c    compute exponential term for plate temperature calculations.
```

```
      arg=-(ul/mce)
      exptrm=exp(arg)
c  compute fr, heat removal factor for this collector.
      fp=f(n)
      fro=frt(n)
      eps=.001
      ict=0
   13 continue
      etrm=-2.*(fp-fro)/fp
      ict=ict+1
      frn=(fp*fp/(2.*(fp-fro)))*(1.-exp(etrm))
      test=frn-fro
      fro=frn
      test=abs(test)
      if(ict.ge.100) go to 14
      if(test.gt.eps) go to 13
   14 continue
      fr=frn
c  set mass flow rate
      flo=fp*fp*ul/(2.*cpc*(fp-fr))
      flow=flo*ac
c calculate design outside film coefficient
      vc=0.25*vdesn*.4344881
      fc=67.049*(vc**.605) +14.0
      fc=1./fc
c  set absorbtivity of collector plate (copper, tube-in-sheet,black.
c  non-selective coating).
      absor=0.95
      return
      end
```

```
      subroutine angle(sinph,cosph,tanph,sinb,cosb,sins,coss,
     1day,time,theta,alpha,answs,answe,answw,answr,
     1samin,answw,ph,sins,costh,cdelt,sdelt)
c
c******************************************************************
c   This subroutine computes angles used in solar calculations.
c
c   It requires that the subr initial compute the following:
c
c       sinph,cosph,tanph - the sin,cos,tan of the latitude.
c
c       sins and coss - the sin and cos of the azimuth angle
c       of the surface for which the incident solar angle is
c       desired.  Angles east of south are positive and west
c       of south are negative.
c
c       sinb and cosb - the sin and cos of the tilt from hori-
c       zontal of the surface for which the angle of incidence
c       is desired.
c
c       day and time - day is the number of the day of the year,
c       and time is the time of day on a 24 hour clock basis.
c
c       It returns the following:
c
c       Theta - the angle of incidence on the surface.
c
c       Alpha - the altitude of the sun.
c
c
c       answs -   angle of  incidence  on the
c                 south wall of the structure.
c
c       answw,answe - the angles of  incidence
c                 on the east and west walls of the structure.
c
c       answw,answr - the angle of incidence on the north
c                     wall and roof.
c
c        these angles used in later calculations of radiation
c        and solair temperature and are set equal to pi/2 if
c        >pi/2. This is done so that calculations taking the
c        cosine of the angle of incidence will be 0 if the
c        angle is > pi/2.
c
c
c******************************************************************
c
      radcon=.01745329
c   compute hour angle.
      h=-6.28319*(time-12.)/24.
      cosha=cos(h)
      sinha=sin(h)
c   compute cos of incidence angle on collector and sin of solar altitude.
      costh=sdelt*sinph*cosb-sdelt*cosph*sinb*coss
      costh=costh+cdelt*cosph*cosb*cosha+cdelt*sinph*sinb*coss*cosha
```

```
      costh=costh+cdelt*sinb*sina*sinha
      sina=sinph*sdelt+cosph*cdelt*cosha
      alpha=arsin(sina)
      if(alpha.le.0.) go to 6
c  compute incidence angle on all house surfaces.
      theta=arcos(costh)
      an2=ph*radcon+1.5707963
      an=ph*radcon+samin
      can=cos(an)
      san=sin(an)
      can2=cos(an2)
      san2=sin(an2)
      cosnr=can*cdelt*cosha+san*sdelt
      cosnw=can2*cdelt*cosha+san2*sdelt
      cosws=-sdelt*cosph+cdelt*sinph*cosha
      coswe=cdelt*sinha
      cosww=-cdelt*sinha
      answw=1.570796
      answe=1.570796
      answs=1.570796
      ansnr=1.570796
      ansnw=1.570796
      testw=abs(cosww)
      teste=abs(coswe)
      tests=abs(cosws)
      testn=abs(cosnr)
      test5=abs(cosnw)
      if(testw.gt.1.) go to 1
      answw=arcos(cosww)
    1 continue
      if(teste.gt.1.) go to 2
      answe=arcos(coswe)
    2 continue
      if(tests.gt.1.) go to 3
      answs=arcos(cosws)
    3 continue
      if(testn.gt.1.) go to 4
      ansnr=arcos(cosnr)
    4 continue
      if(test5.gt.1.) go to 5
      ansnw=arcos(cosnw)
    5 continue
      if(cosww.lt.0.) answw=1.570716
      if(coswe.lt.0.) answe=1.570716
      if(cosws.lt.0.) answs=1.570716
      if(cosnw.lt.0.) ansnw=1.570716
      if(cosnr.lt.0.) ansnr=1.570716
      go to 7
    6 continue
      theta=1.570716
      answs=1.570716
      answe=1.570716
      answw=1.570716
      ansnw=1.570716
      ansnr=1.570716
      alpha=0.
```

```
7 continue
  return
  end
```

```
      subroutine coll(ac,fr,ul,tsold,ta,tpp,flo,cpc,tco,rdn,rht,cc,
     1itype,alpha,theta,beta,rho,qu,ac,rd,rdu,irht,speed,n,uls,qu2,
     1cosb,sina,costh,mce,exptrm,absor,wind,fcc,tsol2,ult,fp)
      real mce
      dimension tau1(3),b(3),slp(3)
      data tau1(1),tau1(2),tau1(3)/.92,.86,.75/
      data b(1),b(2),b(3)/2.3657,2.21143,1.92857/
      data slp(1),slp(2),slp(3)/.02628,.02457,.021428/
c  This subroutine computes the useful energy collected by a
c water heating collector. The plate temperature must rise,based
c  on its heat capacity,heat loss characteristics, and the incident
c  radiation, at least 10 des. c above the temperature of the
c  storage fluid before useful energy is collected.
c
c  the input arguments are;
c        1.   ac - the collector area in meters.
c        2.   fr - the heat removal factor for the collector.
c        3.   ul - the heat loss coefficient for the collector in
c             kJ/sq m-c.
c        4.   tsold - the previous hour's storage temperature.
c        5.   ta - the current hour's ambient air temperature.
c        6.   tpp - the previous hour' mean plate temperature.
c        7.   flo - the fluid mass flow rate (kg/hr).
c        8.   rdn - the current value of the direct normal component
c             of radiation (kJ/sq m).
c        9.   rht - the current value of the global horizontal
c             radiation (kJ/sq m).
c       10.   cc - the cloud cover in tenths of sky coverage.
c       11.   itype - a flag denoting whether or not direct normal
c             radiation values are available;
c                   itype=0 - no direct normal values available.
c                             direct component calculated from
c                             global horizontal and cloud cover.
c                   itype.ne.0 - direct normal values are available
c                   on tape and are not calculated.
c       12.   theta - the angle of incidence of direct component of
c                     radiation, from subroutine angle. (radians)
c       13.   alpha - the solar altitude in radians.
c       14.   beta - the tilt of the collector from the horizontal (rad.).
c       15.   rho - the reflectivity of the surface.(dimensionless)
c
c   the output arguments are;
c         1.   qu,qu2 - the useful energy collected (kJ/sq m).
c         2.   uls,ult - the collector losses
c         3.   tpp the collector plate temperature.
c
      radcon=0.01745329
      if(irht.gt.0.and.irht.lt.9999) go to 8
      rd=0.
      rdu=0.
      rdn=0.
      rht=0.
      go to 6
    8 continue
      if(itype.ne.0) go to 1
    7 continue
```

```
      ckt=0.7*(1.-0.1*cc)
      dbhb=1.-1.3575*ckt
      rdu=dbhb*rht
      if(alpha.le.0.2) go to 2
      rdn=(rht-rdu)/sina
      rd=costh*rdn
      go to 2
1     rd=rdn*costh
      test2=rdn*sina
      if(test2.ge.rht) go to 7
      rdu=rht-rdn*sina
2     continue
      if(alpha.gt.0.2) go to 6
      rd=0.
      rdn=0.
      rdu=rht
6     ac=rd+rdu*0.5*(1.+cosb)+rht*0.5*(1.-cosb)*rho
      tplate=ta+(ac/ul)-(ac/ul-(tpp-ta))*exptrm
      tpp=tplate
      if(ac.le.0.) go to 3
      ttest=tplate-10.-tsold
      if(ttest) 3,4,4
3     qu=0.
      qu2=0.
      ult=0.
      uls=0.
      go to 5
4     continue
      ans=theta/radcon
      if(ans.le.60.) tau=tau1(n)
      if(ans.gt.60.and.ans.lt.90) tau=b(n)-slp(n)*ans
      if(ans.ge.90) tau=0.
      ult=ul*(tsold-ta)
      qu=ac*fr*(ac*tau*absor-ult)
      if(qu.le.0) qu=0.
      uls=ul*(tsol2-ta)
      qu2=ac*fr*(ac*tau*absor-uls)
      if(qu2.lt.0.) qu2=0.
5     continue
      return
      end
```

```fortran
      subroutine strge(ac,flo,au,aload,tsold,tsnew,adump,aaux,
     1strls,ashw,aaxw,vahw,ms,mcps,us)
      real ms,mcps
c This subroutine computes the temperature of the storage fluid   c
c for a solar space heating system based on the useful energy      c
c collected by a flat plate collector, the heat loss character-    c
c istics of the storage vessel, the mass of the storage fluid,     c
c and a control strategy.  Based on the system characteristics     c
c and control strategy, it also computes the uncontrolled heat     c
c losses from storage to the heated structure, the amount of       c
c energy which the collector must "dump" if the maximum storage    c
c temperature is reached, and the amount of auxillary energy       c
c required if the heat load cannot be met from the solar system.   c
      data tmax,tmin/373.16,302.16/
      data strtp,thw/298.16,333.16/
      tsnew=tsold+mcps*(au-us*(tsold-strtp)-aload-ashw)
      if(tsnew.le.tmax) tdump=0.
      if(tsnew.gt.tmax) tdump=tsnew-tmax
      if(tsnew.gt.tmax) tsnew=tmax
      if(tsnew.le.tmin) aaux=aload
      if(tsnew.le.tmin) aaxw=ashw
      if(tsnew.gt.tmin) aaxw=0.
      if(tsnew.gt.tmin) aaux=0.
      if(tsnew.lt.thw.and.tsnew.gt.tmin) aaxw=vahw*(thw-tsnew)
      if(ashw.le.0.) aaxw=0.
      if(aaxw.gt.0.) tsnew=tsnew+mcps*aaxw
      strls=us*(tsold-strtp)
      if(tsnew.le.tmin) tsnew=tsold-mcps*strls+mcps*au
      adump=tdump/mcps
      au=au-adump
      tsold=tsnew
      return
      end
```

```
      subroutine solair(answs,answe,answw,ansnr,theta,tern,
     1ters,teew,teww,tesw,tenw,rdn,rdu,ansnw,v)
c
c   this subroutine calculates the solair temperature for
c   all of the exposed surfaces of the house from the hourly
c   radiation values, the angle of incidence on each surface
c   (calculated in subr angle), the absorptivity for solar
c   radiation for direct and diffuse radiation, and the
c   current value of ambient air temperature.  If no solar
c   radiation is present, the solair temperature is the
c   ambient air temperature.
c
c   set combined radiation - convection heat transfer coef.
c   see ASHRAE guide, chapter 23.
      fcr=42.+15.6*v
c   determine product of fcr and direct normal radiation.
c   a value of 0.7 is used for absorbitvity.
      adrdn=0.7*rdn/fcr
c   determine product of fcr and diffuse radiation.
      rhdu=rdu*0.7/fcr
c   determine solair temperatures for each surface.
      tern=tern+rhdu+adrdn*cos(ansnr)
      ters=ters+adrdn*cos(theta)+rhdu
      teew=teew+adrdn*cos(answe)+rhdu
      teww=teww+adrdn*cos(answw)+rhdu
      tesw=tesw+adrdn*cos(answs)+rhdu
      tenw=tenw+rhdu+cos(ansnw)*adrdn
      return
      end
```

```
      subroutine demand(v,dir,fc,awen,awine,araw,uw,us,teew,aws,awins,
     1adr,ud,tesw,ars,urf,ters,teww,awn,awinn,arn,tenw,tern,auc2,ac,
     1tpp,achw,achs,vol,bls,aub,heatl,winls,hli,ta)
      tr=293.16
c  This subroutine calculates the building heat loss for
c  the house and insulation level specified as a function
c  of temperature, wind, and radiation influences.
c
c  east side
      call fco(v,dir,90.,foc)
      fcoi=1./foc
      uwve=1./(uw+fcoi)
      uawve=1./(uaw+fcoi)
      usve=1./(us+fcoi)
      hle=uwve*awen*(tr-teew)
      if(teew.ge.tr) hle=0.
c  south side
      call fco(v,dir,180.,foc)
      fcoi=1./foc
      uwvs=1./(uw+fcoi)
      usvs=1./(us+fcoi)
      udvs=1./(ud+fcoi)
      urfvs=1./(urf+fcoi)
      hlso=(uwvs*aws+udvs*adr)*(tr-tesw)
      if(tesw.ge.tr) hlso=0.
c  west side
      call fco(v,dir,270.,foc)
      fcoi=1./foc
      uwvw=1./(uw+fcoi)
      uawvw=1./(uaw+fcoi)
      usvw=1./(us+fcoi)
      hlw=uwvw*awen*(tr-teww)
      if(teww.ge.tr) hlw=0.
c  north side
      call fco(v,dir,360.,foc)
      fcoi=1./foc
      uwvn=1./(uw+fcoi)
      usvn=1./(us+fcoi)
      udvn=1./(ud+fcoi)
      urfvn=1./(urf+fcoi)
      hln=(uwvn*awn+udvn*adr)*(tr-tenw)
      if(tenw.ge.tr) hln=0.
c  ceiling-attic losses
      auawe=uawve*araw
      auaww=uawvw*araw
      au2c=auc2/295.16
      aurn=arn*urfvn
      aurs=ars*urfvs
      avsum=au2c+aurn+aurs+auawe+auaww+ac*urfvs
      attmp=tatic(auc2,tern,aurn,ters,aurs,ac,urfvs,ters,teew,teww,
     1auawe,auaww,avsum)
      hlc=au2c*(294.16-attmp)
      if(attmp.ge.294.16) hlc=0.
c  infiltration losses
      v2=v*2.30156
      hli=0.
```

```
      if(ta.lt.tr) hli=(.10+achw*v2+achs*(tr-ta))*vol
      hli=hli*(tr-ta)
c   window losses
      wls=usvs*awins
      if(ta.ge.tr) wls=0.
      wln=usvn*awinn
      if(ta.ge.tr) wln=0.
      wle=usve*awine
      if(ta.ge.tr) wle=0.
      wlw=usvw*awine
      if(ta.ge.tr) wlw=0.
      winls=(wls+wln+wle+wlw)*(tr-ta)
c   total loss
      heatl=hle+hlso+hlw+hln+hlc+bls+hli+winls
      return
      end
```

```fortran
      subroutine shs(ansi,rdn,rdu,insul,shsn,moda)
c  This subroutine calculates the solar heat gain through
c  a window as a function of the angle of incidence of
c  direct radiation, the direct and diffuse components of
c  radiation, and the transmissivity of the window.
c
      dimension tau2(2),taud(2)
      dimension slp2(2)
      dimension b2(2)
      data tau2(1),tau2(2)/0.92,0.86/
      data taud(1),taud(2)/.70,.62/
      data b2(1),b2(2)/2.3657,2.21143/
      data slp2(1),slp2(2)/0.02628,0.02457/
      np=insul
      apfc=.80
      if(np.eq.3) np=2
      np2=np-1
      if(moda.ge.601.and.moda.le.901) go to 1
      ang=ansi*57.2957
      if(ang.le.60.) tauw=tau2(np)
      if(ang.gt.60.and.ang.lt.90.) tauw=b2(np)-slp2(np)*ang
      if(ang.gt.90.) tauw=0.
      cansi=cos(ansi)
      shsn=((cansi*tauw*rdn+.5*rdu*taud(np))*(1.-float(np2)*.10))*apfc
      go to 2
    1 shsn=.5*rdu*taud(np)
    2 continue
      return
      end
```

```
      subroutine fco(v,dir,waz,foc)
c  This subroutine calculates the surface film coeficient
c  according to the algorithm given by Kimura as a
c  function of wind direction and speed relative to the
c  building surface.
c
      rwd=waz-dir
      rwd=abs(rwd)
      if(rwd.gt.180) rwd=360.-rwd
      if(rwd.ge.90.) go to 1
      if(v.le.2.) vc=0.5
      if(v.gt.2) vc=.25*v
      go to 2
    1 continue
      vc=0.3+0.05*v
    2 continue
      foc=67.049*(vc**.605) + 14.0
      return
      end
```